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ROYAL METEOROLOGICAL SOCIETY

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The Evolution of Meteorological Institutions in the United Kingdom

By Sir ROBERT WATSON-WATT, C.B., F.R.S.

(Presidential address delivered before the Royal Meteorological Society on 25 January 1950)

When this Society did me the high honour of picking me out of the curious community of Movieland and Radio to cast me for the rôle of President of the oldest Meteorological Society in the world, I was conscious, as all Presidents-designate must be, of the difficulty of adequately following the very distinguished line of Presidents who have served the Society.

The consciousness of difficulty is tempered by pleasure and pride, and since it is permitted on an occasion like this to be in some small measure personal, even to be invidious, I may be allowed to say that I am particularly sensible of the honour and privilege of following in the succession of two among many great meteorologists. One, whom we are glad to have here tonight, was my father-in-meteorology — Mr. C. J. P. Cave, under whom I first worked as a meteorologist. Indeed it is hardly reasonable merely to say " worked " ; I should rather say " First enjoyed meteorology," under his most kindly, most friendly and most inspiring supervision of the raw newcomer. The other was that superlative star of the meteorological firmament, Sir Napier Shaw, whose magnitude we have not yet measured or adequately appreciated. We, as a Society, have exceptional responsibilities. Of these, the greatest is, I believe, the one we are fulfilling by fitting important elements of detail into that general structure of dynamical meteorology which was put into amazingly good shape by the work of Napier Shaw and those whom he led, formed and inspired.

The man from Movieland, faced with a new production, knows that he is going to have difficulty about a script, and when he has solved that difficulty, he is going to have difficulty about a title. I might, in preparation for this Address, have tried to learn a little of the great deal which is now being done in the branch of meteorology in which I once specialised, but there the script could be so much better written by others, and as for the title I could not face the prospect of having to use that dreadful word " Spherics ".

So I asked myself " How long is it since the Society talked about Meteorology — not about bits of meteorology but about meteorology as a whole ? " Here was an acute problem of title ; I could not venture to offer to this learned gathering an address purporting to fit the title " Meteorology," nor even one on " Meteorology

in the last hundred years," since that would comprehend almost all that we now recognise as meteorology. I might have ventured, not with complete impunity, on a long-range forecast about " Meteorology in the next hundred years." Since the value of history is to help us to avoid repeating our past mistakes, I had it in mind that the synoptic chart behind such long-range forecasting is the story of " The evolution of meteorological institutions in the United Kingdom " — and elsewhere. I trust that I did not in this choice of title mislead you into expecting from me at this, the opening of our Centenary Year, any orderly, complete and authoritative history.

We shall have other and early opportunities of hearing the history of our Society ; how its predecessors evolved and merged into the Royal Meteorological Society. We shall hear again what John Ruskin said in 1839 ; he said wiser things about meteorology than about some subjects more usually associated with his name. We shall, I hope, be reminded of the fine record of the Scottish Meteorological Society, which was set up on the initiative of the official " consumer," the Registrar General ; of Greenwich Observatory, which ten years ago passed its centenary as a source of continuous and comparable meteorological observations ; of Kew Observatory, to which the navigator owes so much that is complementary to the work of Greenwich. We shall remember our debt to the British Association, to whose catholicity, wisdom and sustained zeal Greenwich, Kew, and the National Physical Laboratory all owe much. We shall remember the munificence with which Gassiot assured the future of Kew by an endowment of £10,000 when the Association was compelled to withdraw its grant. And it will not be by the name of Gassiot alone that we shall be reminded of the debt which our science owes to the Royal Society of London.

Any consciencious review would carry us into a survey of the somewhat unbalanced picture of the schools of meteorology in this country — unbalanced, for example, in the distressing air of insecurity, which is more apparent than real, surrounding the " non-permanent " readerships in Meteorology and Geophysics in our two senior universities, in the dual burden of " Astronomy and Meteorology" on the reader at Aberdeen, in the happy unbalance by which London University saves the United Kingdom from disgrace by its provision of a Professorship, and two Readerships in that school of meteorology which worthily continues and expands the tradition of its great founder Napier Shaw.

It is, indeed, that school at Imperial College which justifies the plural when I refer to " permanent " Meteorological Research Institutes in the United Kingdom. The evolution of an officially recognised Research Institute within the Meteorological Office is an astonishingly late growth, but we may well congratulate ourselves on the co-operation and healthy interaction of the governmental Institute and that of the Imperial College. It must be a source of pride to us all, and especially to those who, in the Meteorological Office, in Imperial College, in London University and in the Royal Society worked so hard to establish the school. The school has well earned the tribute recently paid in a recommendation of the Gassiot Committee. That committee urged that the support available for a Meteorological Research

Institute should primarily be concentrated on the Imperial College school, in which Sir David Brunt has so fruitfully laboured from the moment when he first helped Napier Shaw to give it life.

No review of meteorological institutions in the United Kingdom would be complete without a study of private enterprise in meteorology. When Galton, in an official hearing in 1877, said to the representative of the Scottish Meteorological Society " Then the great success of your Society depends mainly upon the exertions of six or seven individuals," he was dealing with a particular case of a general truth. The Phenological Reports of our own Society are a monument to the exertions of a few individuals ; it is an essential part of the evolutionary process that we should look at these reports, to see whether the avenue we have opened up in phenology is now leading smoothly into a wider avenue, along which the biologist and the meteorologist together can carry the observational exertions to an interim goal of scientific understanding and technological application. The British Rainfall Organization, for which G. J. Symons had, as early as 1876, modest financial support from the British Association, was nursed to maturity by our Society and is now a firmly established element in the State Meteorological Service. The Survey of British Thunderstorms is a particularly interesting example of the best kind of private enterprise in meteorology. It was initiated by C. J. P. Cave in the 1915-16 period, and it made some notable and surprising contributions to our knowledge of the meteorology and climatology of these Islands. I greatly admire the devotion and pertinacity of Mr. and Mrs. S. Morris Bower, who have devoted a large part of their lives to carrying forward the work of the Thunderstorm Survey, and who have won steadily increasing warmth in the initially rather tepid approval accorded to the Survey.

I wish I could say something useful about the principles and practice of that private-enterprise forecasting which is now front-page news ; I suggest in all seriousness that the Society should in its centenary year aim at hearing some account of the way in which those daring and widely publicised long-term forecasts are made — and how well or ill they stand up to retrospective scrutiny.

Thus far I have been talking about the things about which I am not to talk ! Thus late I reach the question which has not, so far as I can judge, been posed in any Presidential Address in the last thirty years. What is the state of our science and our art ; what are we doing to ensure their healthy progress ? This Society has, I believe, a peculiarity not special in kind to itself, but special in relative importance. Meteorology is the science of the atmosphere ; science is, according to the dictionary, ordered knowledge.

Now ordered knowledge about the atmosphere is of profound interest, not only to the people who want to pursue the knowledge in an austerely scientific way, those who pursue it as an exceptionally difficult form of physics conditioned by the vagaries of water in the atmosphere, but also to those who are interested in meteorological phenomena as elements in nature study, to those to whom the application of the science of meteorology is of economic value, to those to whom the applications of meteorology form a substantial part of that uninterrupted progress

of civilisation which goes on even in these doubtful years 1949/50, and to those to whom every meteorological state is a picture. One of the troublesome things about meteorology is that it is profoundly interesting to everybody who has to live on this planet of ours, and that for a great variety of intellectual, practical and aesthetic reasons.

This was clear in the year 1877 to an Official Committee, to which an ex-Hydrographer of the Navy said : " Everyone has a finger in the less exact science of meteorology ; and I shall be very sorry for the Hydrographer to have, in addition to the responsibilities of the Hydrographic Office, half a dozen societies or amateurs in all parts of the kingdom teaching him his work."

It may be a difficulty ; I believe it to be an exceedingly healthy thing for the Hydrographer or the Director of the Meteorological Office (" The Meteorologist Royal") that there should be half a dozen societies and a much larger number of amateurs, all indicating a profound and critical interest in how he does his work. We have long passed the 1877 stage — " if it were possible that it could all be done by one Government department I think it would be very much better." We have passed the stage where it could be said that " the graphic results are of a dilettante character ; and however clear or ingenious, won't come into general use among seamen." We have got past the stage when it could be said " I am not much in favour of International work of any kind ; I think it rarely answers." Those of us who have dealings with modern international organisations may in our weaker moments say " He's got something there," but the weak moment passes. We have to thank the pioneers of meteorology in particular, that their pioneering during the fierce fighting early days of the Meteorological Office carried us beyond the then Astronomer Royal — " —— left, as I am afraid we shall always be left, in merely an empirical state." So much for 1877, what are we doing about our science in 1950 ? Who are the Fellows of this Society ? They are without exception amateurs and dilettanti, in the original and genuine sense of these words. I believe there is nobody who devotes his attention, professionally or otherwise, to meteorology, who is moved by any other primary impulse than that he loves the subject ; the meteorologist, the Fellow of this Society, is certainly a lover, and one who takes delight in his subject. Amongst these amateurs are many classes, those whom I may with deep respect call the academic professionals, those who are the official professionals, in the Meteorological Office in particular, those who are the students, the most important of all the members of the meteorological community — all lovers of the subject, and all exercising their profession only because they love their subject. There are the consumers of meteorological information, the public utility officers and the like, and there are those to whom we too readily confine the title of amateur in its more recent sense.

Why did such people gather themselves into a Meteorological Society a hundred years ago ; why do such people subscribe to maintain and expand such a society; what are the functions of the Society ?

The success of the science of meteorology in revealing the fundamentals behind the ordered knowledge of the atmosphere is in danger of obscuring the general

view of the functions of the Society as they were a hundred years ago, as they ought to be in the next hundred years. The original functions were in part those of facilitating and ensuring systematic observations, and the distribution of information. We have with appropriate diligence set up observing stations where persons of strictly amateur status, at no inconsiderable discomfort to themselves, ensure accurate, standardised and punctual observations in a network which now extends over the whole of the civilised world. Our founders were conscious of the importance of an organisation such as ours in ensuring the distribution of meteorological data and of meteorological knowledge, which I would differentiate by saying that knowledge is information which has, at least in part, been digested. I have referred earlier in this meeting to the state of the Society's library ; I would say now that the library is a symbol of a major responsibility of the Society, laid on us by our predecessors. Council attaches the utmost importance to ensuring that this Society should maintain a comprehensive, worthy and easily accessible library, not merely for the Fellows, but for all amateurs of meteorology, a library which should be better than any other meteorological library in this country. I would like to feel that when somebody wants to study in meteorology, he should be able to do it in comfort, in freedom and with a sense of belonging to the true amateur tradition ; that for any bit of work he should be able to turn confidently to 49, Cromwell Road, where he would find his material and where he could work on it. The Society was, too, throughout the greater part of its first 100 years, a nurse for new enterprises, which in turn grew up out of the nursery and took adult status. In a troubled world it is well to keep a close eye on the children who are growing up to be nearly self-supporting, and the most important continuing duty of the Society is to make provision for discussion and publication of original documents. Nothing has given me greater pleasure, in my return to the meteorological fold from which I strayed some considerable time ago, than to observe the very high quality shown in originality, initiative, and in judgment as to the appropriate points to be chosen for attack, by the communications, particularly in dynamical meteorology, which we have discussed and published during these few post-war years.

I know that the most professional of the professional meteorologists believe that their work owes a great deal, and will continue to owe a great deal, to the freedom with which they can bring their finished work — and still more important, their unfinished work — to this meeting room of the Society (this slightly inconvenient and limited meeting room) sure that they will be doing at least three things in bringing their communications here. They will be deriving a great deal of wise comment alike from their peers and from those who can look on from the sidelines and see much of the game as a whole. They will be doing a great deal towards the enlightenment of the public. In particular they will know that we are providing an advanced training ground for those serious students whose numbers are continuously growing. This Society has, at one end of the scale, the job of encouraging the beginner, and at the other end, as we have been doing this evening, recognising the achievement of the master.

All this we have done in our first century ; what are the things that we ought

to be thinking about in our second hundred years ? How can we still further accelerate the progress of dynamical meteorology ? It may well be that the Society should concern itself, much more than it has done in the past, in keeping an encouraging watch on the provisions made for meeting the greatest deficiency in all meteorology ; the deficiency of an adequate number of adequately skilled physicists engaged in meteorological work. Then, having done something towards stimulating the flow of trained people or of partly trained people it has a duty to look critically, even sceptically, at the organisation of the work of those meteorologists, within the exalted sphere of the State Meteorological Service as elsewhere.

I do not suggest that this Society should concern itself directly with the economic conditions of professional meteorologists. I do suggest that we must look at the way in which the professional meteorologist is fitted into the rigid or rigidifying organisation as it grows, to make sure that no avoidable imperfections, which react against encouraging the recruitment of newcomers, present themselves. We have, not infrequently, but certainly not frequently enough, had other kinds of valuable discussion — we have two examples in the 1949 agenda — joint discussions between the meteorological interpreter and the person who has the good or bad fortune not to have intimate knowledge of meteorological data but to have his daily work greatly affected by the weather, meetings between the provider and the user of meteorological knowledge. Such joint discussions should be more frequent than now, difficult as it may be to find time for still more meetings.

On balance, however, dynamical meteorology is making a pretty good go of looking after itself. Can we say the same of what I may loosely call Biometeorology ? In it there has, in the last hundred years, been no spectacular advance comparable with that of dynamical meteorology. The full utilisation of meteorological science in respect of the effects on the living organism of weather and climate should be given a much larger share of attention than has fallen to it, and that only in a very few recent decades. It is not only in agriculture — the primary industry of this country and of the world, the neglect of which is a much greater menace than are the recent products of the physicists — that there is a pressing need for a closer co-operation with, and for a much wider service from, the meteorologists. We have had much talk in political circles, cultural circles and aviation circles, about the five freedoms, and it may be a useful mnemonic — I apologise for offering a slogan — to set ourselves a task for the first decade of our second hundred years. We who are concerned with the effects of climate and weather on daily life are also concerned with five freedoms ; freedom from starvation, freedom from thirst, freedom from dirt, from disease, and from discomfort. All these freedoms are dependent on adequate and pure water supplies, and they are by no means assured freedoms, even in this metropolitan area ; they are not assured freedoms in the city of New York. The dangers of a failure in our water supply are not imminent, but they are not absent from the United Kingdom ; they are pressing in New York and extremely pressing in the state of California. How precarious is the balance of our national and local provision for copious clean water supplies should be recognised before it forces itself unpleasantly on our attention. To ensure that

meteorological contributions are properly measured to these absolutely basic needs of every human being is quite as worthy a task as any we set ourselves in our first century.

When I ask myself the question " When did we last discuss meteorology ? " I rebuke myself for over-generalisation and I put myself a more limited and more precise question, " Have we ever met to discuss the Annual Report of the Meteorological Committee to the Secretary of State for Air ? " It is true we mention it in our publications, but it is equally true that, indispensable as publications may be, the written word is ordinarily inferior to the spoken word for eliciting a common measure of wisdom. It might be a good thing to pick up such a document as *M.O.* 25, H.M.S.O., 9d. net, to see whether it suggests some of the things which we are not doing adequately in the fulfilment of our care for meteorology. What do we find ? We find at Page 5 the statement that " the Meteorological Office is the State Meteorological Service." We have here a reasonably balanced answer to the difficulties of 1877. We have a State Meteorological Service of which we are justly proud. But we have avoided the folly of attempting to absorb into it the one or two thousand amateurs who can better from outside help the State Service in the almost impossible task which is put upon it. On the same page is a statement of the functions of the State Meteorological Service, a statement which is of special interest in relation to the encouragement given to professional meteorologists, since the progress and advancement of meteorology is their life, their career. It appears that the duties of a Meteorological Office include the provision of meteorological services to a number of organisations — which do not include the Royal Navy. The Office " maintains liason with " the Naval Meteorological Branch, and " provides it with basic information." And the Office conducts research in meteorology and geophysics. This last, and astonishingly recent addition to the list of duties, ended the curious anomaly that the professional was expected to do his research as a leisure relaxation, by candle-light, so to speak, after a day spent in the accumulation, comparison and presentation of facts.

We had not in 1915, when I joined the Meteorological Office, progressed very far from that period 1858-74, in which the Treasury and the Royal Society gravely doubted whether the State Meteorological Service should go beyond the presentation of facts, whether it were " advisable to utilise them while manageable rather than to continue a mere accumulation, at the risk of being confused if not overwhelmed," when there was a feeling that " the Government could not take the responsibility of drawing conclusions." It was with a real lift of the heart that so lately as 1939 we received an Annual Report which announced provision for the introduction of organised research into the normal work of the Meteorological Office. Ten years ago, provision was thus made, apparently for the first time, for official as opposed to personal research in meteorology. Here was the effective foundation for that governmental Meteorological Research Institute to which I referred in my preamble. I think we have reason for pride in this, however belated, advance from the dark ages ; the State at last recognising its direct duty to proceed from accumulation to interpretation, to give real encouragement, by way of facilities

and organisation, for the building up of a body of meteorological knowledge rather than of meteorological data. The work which has been done by the State Meteorological Service since those days has been of a kind which reinforces our gratitude to the Royal Society of London and to the Gassiot Committee of that Society, for the share that they have taken in deciding which of many desirable and promising long-term researches should, in fact, be encouraged by the State Service. And in part payment I believe we can assert with confidence that the Fellows of the Royal Society, who have contributed so much in the meteorological sphere in past years, will find worthy successors within the group of professional meteorologists now active in the work of our Society. It is clear from our recent discussions and contributions that alike among the academic and the official professional meteorologists we have young workers who, within a very small number of years, will make contributions to meteorology which the Royal Society of London will be proud to accept and to honour ; a future supply of meteorological Fellows of the Royal Society is assured.

Turning again to the Report, I observe references to international work, and I wonder when we last discussed I.M.O., what we know of the W.M.O. which is to come ; whether we as a Society have not something to contribute from our general experience of how to get the best out of international meteorological bodies. We remember that our international meteorological organisations were pioneers of international co-operation, among the earliest and among the most harmonious and constructive of unions of nations. Yet our pride is tempered by the knowledge that such world organisations do not automatically work well and objectively. Many of us who have worked in other spheres of international co-operation know that we are not yet at a stage where world organisations operate without friction, frustration and stagnation ; we know that to persuade fifty nations that they all think the same thing is quite a considerable enterprise. And we know that good international decisions can only be ensured when each delegation has behind it the considered judgments of the informed amateurs on the professionally prepared statement of national views.

Later in the Report we come to the cost of the Meteorological Office — it costs something like 8¼d. per head of our population — in 1898 it was estimated, in a presidential address, to be costing one-third of a penny *per annum* per head of the population ; neither figure is enough — 8¼d. is in fact a retrogression below the 1898 standards. In 1898 the national expenditure fell just short of £100 m., while in present years it is of the order of £3,000 m. It would appear that we should, *ceteris paribus*, now be spending something like 11d. per head *per annum* on the Meteorological Service. But in fact other things are far from equal ; for the problems of aviation, for example, were then of a pristine simplicity, and however clear the need for upper air data may then have been, the technical means of satisfying the need did not exist. We are still starved of upper air data, and there again the views and advice of the Society should be strengthening the hand of the official custodians of meteorological interests. I found it a little odd that we left it to a joint meeting of the Royal Aeronautical Society and the Institute of Navi-

gation, discussing navigational aids, to put the highest emphasis on the unsolved meteorological problems which face the modern aeroplane operator.

We find in the Report an interesting list of clients of the State Service, but with only one clear recognition — in the case of the British Electricity Authority — that there is in peacetime operations, as in war, need for an informed " middleman " to sit with the consumer to help him to discover what he really needs. Meteorology is I am sure one of the many applied sciences which require the help of operational research in their service to peacetime industry. Would it not be profitable to devote at least one of our meetings to the examination of that need ?

We naturally find, in the document, reference to forecasts and weather reports which are distributed through the medium of the B.B.C. Ought not this Society to consider whether these 5-minute snippets interspersed in the broadcast programmes are, in their form, their duration, their timing and their frequency, well measured to the duty of the State Meteorological Service, to the duty of the State Broadcasting Service and to the needs of the community at large? It is for discussion somewhere ; where better than here ?

The Office gives services to a Royal Air Force which would appear to have discovered the value of having civilians around to do professional scientific work, of a kind which is in great measure common to many services but requires special adaptation to the needs of each. But the corresponding services for the Royal Navy would appear to be performed by a Naval Meteorological Branch " responsible for the administration of meteorological work in the fleet." I am handicapped by ignorance of the point (if it exists) where the administration of meteorological work ends and meteorological work begins. But I doubt whether meteorological work for the fleet can be adequately performed save by one who has chosen meteorology as his life career. I doubt whether any separate service is capable of offering a career which will carry him through to a fair ceiling and in which he can make the best scientific contribution to meteorology of which he is capable. Do the conditions of a separate service offer as much encouragement as that which would be given by a really general State Meteorological Service to the solution of that primary problem of national meteorology, the recruitment, training and full utilisation of scientific meteorologists ? I do not offer, out of my ignorance, a snap answer, but I pose the question for discussion.

Nor can I leave this question of the encouragement of the scientific meteorologist without calling attention to the distressing figures in the Report which deal with the establishment and strength of the Meteorological Office. There is an establishment of 2,714 permanent officer posts — there are now 1,426 permanent officers on the strength within this gravely under-manned establishment, and there is a substantial net loss in the officer grade for the year under review. These are indications of a serious disease in the professional body ; it will not be cured without the help of the amateurs and the dilettanti. We must have more physicists specialising in meteorology. This Society and sister societies ought to be giving a good deal of thought and discussion and comment to this need among the many needs for more physicists. Perhaps we shall not look in vain for " Meteorology

in the United Kingdom" in the report of the next Commonwealth Scientific Conference !

I venture to criticise some of the items in the Annual Report on the Meteorological Office because I am proud of my old Office ; doubly proud of the great vigour of its present work. It is not that pride alone which leads me to believe that the gross expenditure on such a remunerative investment should be increased ; but I shall be still more proud of the greater service which will result. The price of a good state service anywhere is eternal vigilance ; and the major share of that constructive vigilance and its expression should come from outside the state service but from inside the assembly of the amateurs.

If we ask for the understanding and the co-operation of more and better physicists in the fuller pursuit of meteorological geophysics, we do so the more confidently because of the unfailing law of retroaction, of beneficent feedback from the immediate beneficiary to the immediate benefactor. We remember that the demands made on Fessenden by the U.S. Weather Bureau for wireless telegraphy as a vehicle for synoptic weather reporting gave us, as a mere by-product, a successful demonstration of radio-telephony at the incredibly early date of 1900. We remember that the radio location of thunderstorms contributed something to the development of radar, and that radar has repaid that particular debt by contributions to wind finding. We remember that the anomalies of centimetric radar gave a fresh stimulus in meteorology by demands — not yet fully satisfied — for studies in the micro-meteorology of radio ducts in the lower atmosphere.

I am conscious that on this eve of a General Election this address may have taken something of the colour of an election address. I am certainly seeking a mandate. I am convinced that in entering our second century we must re-examine our responsibilities and undertake tasks which are old in kind but new in magnitude. No Council, however highly qualified, enthusiastic and diligent, can of itself answer such questions as I have, by way of illustration, posed this evening. Every new Council takes up its duties with a sharp sense of the losses of wise counsellors which are due to the normal passage of the years. I appeal to individual Fellows to help the new Council in two particular ways. First by individual comment on the suggestion which I have dared to make, that we should draw fresh inspiration from the care which our predecessors of a century ago gave to meteorology as a whole as well as to its parts, and secondly by a willingness to serve on the considerable number of *ad hoc* committees which I believe will be required if, as I hope, the Society enters on its second hundred years with a determination to remember constantly that the burden which it voluntarily assumes is no less than the inspiration, expansion and application of the science of meteorology and climatology in the service of man.

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The bright band — a phenomenon associated with radar echoes from falling rain

By J. E. N. HOOPER and A. A. KIPPAX

(Manuscript communicated by A. C. Best, M.Sc., 13 May 1949)

Summary

Frontal rain when illuminated by radar transmission gives rise to echoes which exhibit a characteristic layer of greater intensity near to the freezing level. Observations which establish the height of this layer or " bright band," relative to that of the freezing level, are described. Measurements of the terminal velocities of snowflakes of known mass, a factor of importance in support of a possible explanation of the phenomenon, are also given.

1. Introduction

The authors have published elsewhere (1950) an account of their work on the nature and intensity of radar echoes from rain and snow. One important feature of this study was the appearance of a " bright band " ; a horizontal layer within the rain echo from which the echo intensity is greater than from any other part of the precipitation. In determining the height of this layer and its possible cause, subsidiary experiments were carried out, only a summary of which is quoted in the paper already referred to. It has been suggested that the details of these experiments should now be made available.

2. The bright band — a possible explanation

When a radar set is directed vertically into falling rain the echoes therefrom are characterised by the occurrence of an intense echo at a height a little below the freezing level (see Fig. 1). This echo is more pronounced in frontal rain than in instability showers and is of the order of five to nine times more intense than that from the rain below (when both intensities have been normalised to equivalent ranges), as is illustrated in Fig. 2.

Ryde (1946), assuming that the particles have their origin as ice crystals, points out that as these crystals or flakes fall into warmer surroundings below the freezing level, two consequent effects will modify the reflectivity of the particles and the intensity of the echo derived therefrom. In the first place, the change from ice to water will result in an increase in the reflective properties of the particles so that the echo intensity will increase. In the second place, the velocity of fall of the flakes is less than that of the resulting water drops so that the number of particles per unit volume will decrease continuously as melting proceeds until all the particles are completely melted and have attained the appropriate terminal velocity of water drops, when a steady state (neglecting any evaporation) will occur in the falling rain. Thus the echo intensity will fall off as the particles accelerate from their velocity as flakes to their velocity as drops. The bright band may ideally be considered to be a transition region of melting particles distributed with the concen-

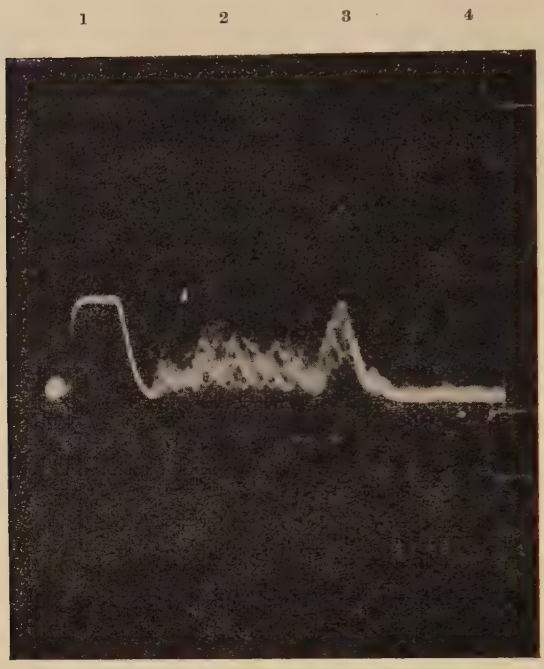

Figure 1. Photograph of Radar A scope during precipitation showing :
(i) ground ray,
(ii) echoes from rain,
(iii) bright band echo, and
(iv) very small echoes from above bright band

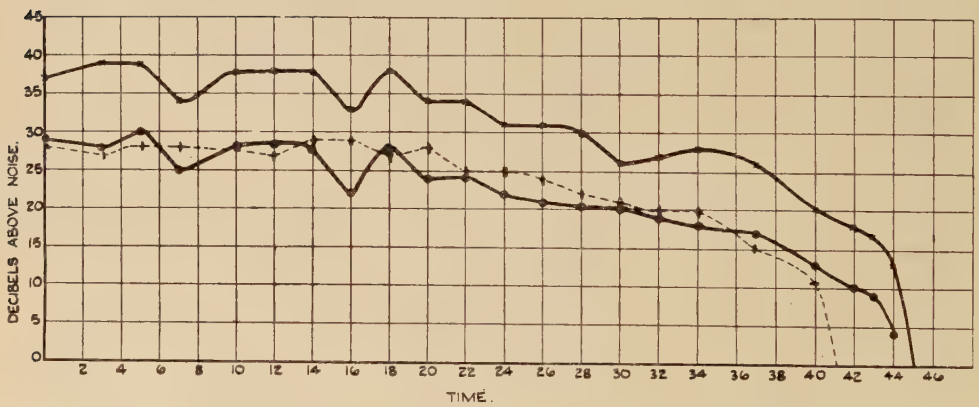

Figure 2. Variation of echo intensities with time during precipitation

x———x Echo from bright band
o———o Echo from below bright band
— — — — Echo from above bright band

Note : All echo intensities normalised to equivalent intensity at 1,000 yards before plotting.

tration of snowflakes, bounded above by a region of snowflakes, and below by water droplets distributed with a concentration less than in the bright band by a factor equal to the ratio of the terminal velocity of a raindrop to that of the snowflake of equal mass. In practice, the boundaries of the bright band will not be so clearly defined though a paper by Cunningham (1947) mentions aircraft observations which provide some confirmation of the existence of these states.

The ratio of echo intensity from the centre of the bright band to that from the rain below has been measured (Hooper and Kippax 1950) and found to lie between five and nine and it will be of interest to investigate the ratio of the terminal velocities of raindrops and of snowflakes to discover whether these two ratios are comparable. It is also necessary to confirm by experiment that the bright band does occur below the freezing level.

3. Height of the bright band relative to that of the freezing level

In order to investigate the relationship between the heights of the bright band and of the freezing level, a vertically radiating radar set on a wavelength of 3.2 cm was taken to Larkhill where radio-sonde ascents are made periodically each day, from which the height of the freezing level was determined. A reduction of 100 feet has been made to the sonde determinations to correct for the lag in the temperature element (Dymond 1947).

In general observations on the height of the bright band were made simultaneously with the radio sonde ascents. On one occasion, however, observations of the bright band were made between sonde ascents. The freezing level had changed by only 400 ft between ascents and the assumption has been made that this slight change was linear with time, so that an interpolated freezing level has been used for comparison with the height of the bright band determined between the ascents.

On a further occasion, it was found impossible to make an ascent at Larkhill. Examination of the data from other parts of the country indicates that the freezing level was probably at a height of between 4,100 ft and 4,400 ft when the bright band was at 4,000 ft.

The results of ten comparisons show that the height of the bright band lies, on the average, some 330 ft below the freezing level where the error of this mean (defined as $\sigma/\sqrt{n}$ where σ is the standard deviation of n readings) is 150 ft.

Apart from the observations at Larkhill, one other occurrence is of interest when at Malvern on 19 November 1946, the height of the bright band was observed to increase in the manner shown in Table I.

TABLE I. Variation of height of bright band with time

Time (G.M.T.)	Height of bright band in feet
1050 — 1109	5,250
1128	5,850
1142 — 45	6,450
1223 — 33	6,300
1400	6,600
1410 — 25	6,900
1428	7,200
1430	7,500
1450	7,500

Radio-sonde ascents established that a warm front passed through Larkhill between 0500 and 1100 hr when the freezing levels were respectively 4,200 and 8,200 ft. Records show that the front did not move along its normal but " side-slipped " so that the front was not detected on the ground at Malvern although it is considered that at the height of the freezing level the front would have reached Malvern some three hours later than Larkhill. The change in height of the freezing level might be expected to be less than at Larkhill because of this " side-slip " movement. The correlation in time between the change in height of the bright band and the expected change in that of the freezing level is further qualitative evidence of the relationship between the two levels.

It would appear from the limited data here recorded that a correlation exists between the heights of the bright band and of the freezing level and that the latter is in general about 300-400 ft above the former. In order to obtain more accurate data it would be necessary to use a radar set employing a narrower pulse width and to take special precautions in the use of the radio-sonde. Such precautions would involve a careful measurement of the time lag of the temperature element in the sonde, and determination of the height of the sonde by radar methods.

4. Ratio of velocity of fall of snowflakes to that of resulting raindrops formed on melting

Comparatively few values of the velocity of fall of snowflakes of known mass have been found. A paper by Nakaya and Terada (1935), however, furnishes some data concerning individual crystals ; from it the following have been extracted.

Crystals have been classified into types of which three have here been considered as relevant to this discussion. It was found that with these three types, the velocity of fall was independent of the flake dimension d which is defined as the diameter of a sphere enclosing the crystal. The mass of the crystal has been found to conform with an empirical expression given in Table II in which the range of d is also specified.

TABLE II

Type of crystal	Mean velocity of fall (m/sec)	Range of d (mm)	Mass (mg)
Plane dendritic	0·30	1·4 — 5·0	$m = \cdot 0038d^2$
Powder snow	0·50	1·2 — 4·4	$m = \cdot 010d^2$
Spatial dendritic	0·57	1·8 — 7·6	$m = \cdot 010d^2$

From these data the diameter of the spherical raindrop produced by melting a flake has been calculated and the terminal velocity of such a drop, obtained from a relation furnished by the Meteorological Office, is given in Table III.

TABLE III

Type of crystal	d (mm)	Crystal mass (mg)	Raindrop diam. (mm)	Term. vel. of raindrop m/sec	Vel. raindrop / Vel. crystal
Plane dendritic ..	2	0·015	0·307	1·33	4·4
	3	0·034	0·403	1·63	5·4
	4	0·061	0·488	2·12	7·1
	5	0·095	0·566	2·47	8·2
Powder snow ..	2	0·040	0·424	1·76	3·5
	3	0·090	0·555	2·43	4·9
	4	0·160	0·674	2·92	5·8
Spatial dendritic ..	2	0·040	0·424	1·76	3·1
	3	0·090	0·555	2·43	4·3
	4	0·160	0·674	2·92	5·1
	5	0·250	0·781	3·32	5·8
	6	0·360	0·883	3·70	6·5
	7	0·490	0·978	4·00	7·0

We see that the ratio of the velocity of fall of a raindrop to that of the crystal from which it is formed by melting ranges from 3 to 8 for individual crystals.

Some terminal velocities of snowflakes are given in the *Meteorological Magazine* (Giblett 1921). Taking 0·05 gm/c^3 as the apparent density of the flakes, the diameters of the resulting water drops have been calculated together with the ratio of the velocity of fall of the drop to that of the flake and are given in Table IV.

TABLE IV

Type	Flake: Approx. diam. (in.)	Flake: Vel. of fall (m/sec)	Water drop: Approx. diam. (mm)	Water drop: Vel. of fall (m/sec)	Ratio Vel. drop / Vel. flake
Large ..	0·75	1·8	7	9	5·0
Medium	0·5*	1·5	4·7	8·8	5·9
Small	0·25	1·1	2·3	6·9	6·3

* assumed

During falls of snow in early 1947, the authors carried out a few observations on the velocity of fall of snowflakes, and although the method was somewhat crude because of the hasty preparations, it is felt that the results should be placed on record as giving some idea of the order of magnitude. The method of timing by using a stop-watch and the length of path (2·3 m) over which the timing was effected are similar to those employed by Nakaya and Terada. The timing was carried out in the open at temperatures below freezing and at such times as turbulent conditions appeared to be negligible. While one observer was timing the fall, another observer was engaged in catching individual flakes on a black cloth and compressing each. The compressed mass was brought into a warm room, allowed to melt and immediately dropped on to blotting paper treated with dye, where a stain was produced. The diameter of the stain was measured in two directions mutually at right angles and the drop diameter corresponding to the mean stain diameter obtained from a calibration chart which had been prepared by using drops of a known diameter produced from specially made brass tips. The terminal velocity of the drop of mean diameter was obtained as before and the ratio of this velocity to the mean velocity of fall of the flake calculated. The results of the experiments performed on three occasions are given in Table V.

TABLE V

Series	Mean time of fall of flake (sec)†	No. of obser-vations	Mean vel. of fall of flake (m/sec)†	Resulting mean drop diam. (mm)†	No. of obser-vations	Terminal vel. of drop (m/sec)†	Ratio $\frac{\text{Vel. drop}}{\text{Vel. flake}}$ †
1	3·14 ± ·05	100	0·73 ± ·01	1·72 ± ·05	16	5·96 ± ·10	8·2 ± 0·3
2	2·65 ± ·06	50	0·87 ± ·02	1·30 ± ·06	25	4·97 ± ·16	5·5 ± 0·3
3	2·15 ± ·08	34	1·07 ± ·04	2·39 ± ·06	5	6·97 ± ·08	6·5 ± 0·3

†—In each case the standard deviation is also given.

That the technique of compounding the flake in the manner described and allowing the drop to fall on to the blotting paper is reasonably sound is shown by a subsidiary experiment when flakes were collected as before, but before being compressed, the number of individual crystals comprising the flake was counted. The resulting stain was measured, the drop diameter obtained from the calibration chart and the volume of the drop calculated. A plot of the volume against the number of crystals per flake gives a very linear relationship as might be expected if the technique were sound. The results are shown in Fig. 3.

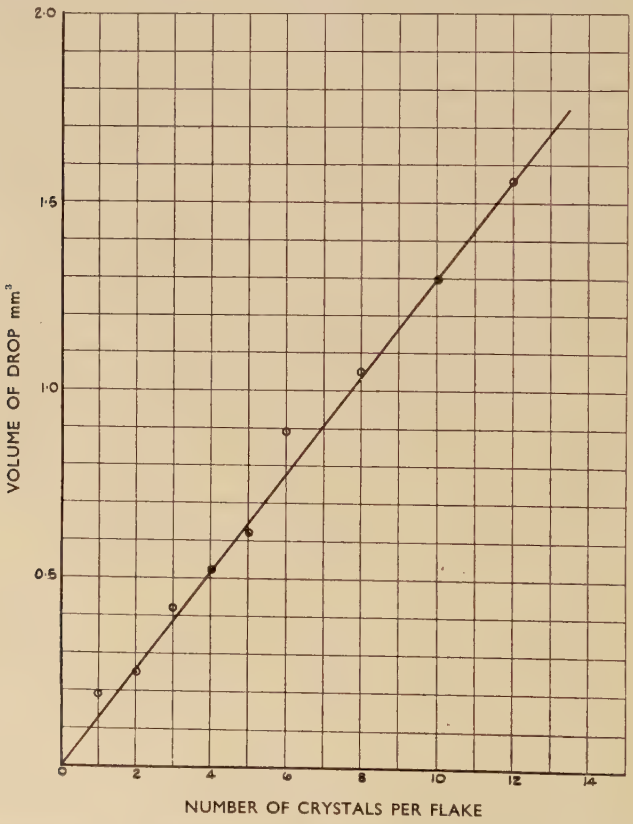

Figure 3. Dependence on number of crystals per flake of volume of drop resulting from melting flake

The values tabulated above are for the ratio of the fall velocity of a raindrop to that of the snow crystal or flake of equivalent mass are, it is evident, spread over for the same range of values as the ratio of echo intensity from the bright band to that from the lower rain. This evidence gives considerable support to Ryde's suggestion that the reduction in echo intensity below the bright band is occasioned by the acceleration of the water droplets from their velocity as snowflakes to the terminal velocity of raindrops.

5. Depth of the bright band

Laws (1941) has shown that a raindrop of medium size falling from rest acquires its terminal velocity in a distance of about 10 m. Since in the bright band the processes involve melting as well as the acceleration of the drops, it may be presumed that the bright band extends vertically over a thickness much greater than this. The bright band echo was observed to be of the order of 2·5 μ sec duration using a set with a pulse duration of 1 μ sec so that the depth of the bright band appears to be about 750 ft.

It may be of interest to record that on one occasion when the 0°C isotherm lay at a height of about 500 ft above M.S.L. at Malvern, the authors explored a snow shower in height by descending the Malvern Hills when it was observed that whereas only snow was falling where the temperature was within half a degree of the freezing point, almost only rain was simultaneously falling at a level some 200 ft lower. On this occasion the drop size was rather small and the flakes would have quickly melted and acquired their terminal velocity. The transition region was too low to be explored with the radar set.

6. Conclusions

The magnitude and position of the echo from a horizontal layer of increased intensity, within rain echoes, is shown to be such that it lies a little below the freezing level and is some five to nine times as great as the echo from the rain below. This conforms with a suggestion that the more intense echo is derived from a region of water drops formed by the melting of ice crystal aggregates from above, but with a concentration more nearly equal to that of the aggregates, since they have not attained their terminal velocity as water drops, than to that of the lower raindrops.

7. Acknowledgments

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The application of the similarity theory of turbulence to atmospheric diffusion

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(Manuscript communicated by P. A. Sheppard, B.Sc., and received 7 October 1949)

Summary

The purpose of this paper is to draw the attention of meteorologists to the potential usefulness of the similarity theory of the small-scale structure of turbulent motion first put forward by Kolmogoroff. An outline of the theory is given first and the possibility of its application to atmospheric and oceanic turbulence is considered. As an example of its use, the theory is applied to the problem of the relative diffusion of neighbouring particles moving with the fluid, and predictions about the rate of increase of mean square distance between the particles are made. Some data obtained recently by Durst are compared with these predictions by Charnock, and similar observations made by Richardson and Stommel are considered herein. The empirical proportionality between the diffusion coefficient and the 4/3 power of the scale of observation, obtained many years ago by Richardson, is shown to be in general agreement with the theory.

1. Introduction

In 1941, A. N. Kolmogoroff (1941a and b, Batchelor 1947) introduced a set of hypotheses about the small-scale structure of turbulent motion. Since then other people (Onsager 1945, Weizsäcker 1948) have put forward the same ideas, which have been accepted widely for their *a priori* plausibility. The theory concerns the nature of turbulent motion at infinitely large Reynolds number and the evidence derived from wind tunnel experiments does in fact indicate that the predictions of the theory become more and more accurate as the Reynolds number is increased. It seems reasonably certain that, at the Reynolds number of turbulent motion likely to be encountered in the atmosphere or ocean, the theory provides a substantially valid statistical description of the small-scale structure of the motion.

It is thus natural to ask if the turbulence in the atmosphere and the ocean is such that the similarity hypotheses are applicable. If so, are there any meteorological problems in which the similarity theory would provide useful information ? These are the questions to be considered in the following paper. We begin by recapitulating the ideas of the similarity theory.

2. The similarity theory of the small-scale structure of turbulence

It is an old and accepted idea that the large eddies of a turbulent motion gradually break up into a series of smaller eddies, which in turn pass their energy on to even smaller eddies*. The damping action of viscosity is relatively stronger

* Let it be said firmly and right at the beginning, that the word " eddy " does not refer to any particular local distribution of velocity. It is merely a concise term for a component of motion with a certain length scale, *i.e.* an arbitrary flow pattern characterized by size alone. We are thus imagining the motion to be resolved into a spectrum of eddies of different size. One definite — and practicable — example of such a resolution is an analysis of the velocity distribution into sinusoidal components of different wave-lengths.

for small eddies, so that the breaking-down of eddies does not continue to indefinitely small eddies. The situation is expressed well in the rhyme* attributed to L. F. Richardson :

" Big whirls have little whirls,
That feed on their velocity ;
Little whirls have lesser whirls,
And so on to viscosity."

The new idea put forward by Kolmogoroff is that a kind of statistical decoupling accompanies this transfer of energy from large to small eddies. That is to say, the direct influence of the large eddies is gradually lost as the energy passes down the system of eddies, and the small eddies tend to have properties which to some extent are random. An immediate consequence of this idea is that the small eddies have no directional preferences, on the average, and hence that their motion is isotropic, whatever may be the directional preferences of the large eddies. Townsend (1948) has made measurements in the turbulent wake of a long cylinder, in which there is a very decided lack of isotropy of the energy-containing eddies, and these measurements show that the small-scale structure of the motion is approximately isotropic.

If the average properties of the small eddies are not directly affected by the large eddies, what do they depend on ? One's first hope is that they are the same in all cases of turbulent motion, but this cannot be so. The viscosity of the fluid governs the rate of energy dissipation, the bulk of which occurs in the smaller eddies, so that ν (the kinematic viscosity) is one relevant parameter for the small eddies. A second relevant parameter is the amount of energy handed down from the large to the small eddies, for the small eddies must adjust themselves so as to convert all this energy into heat. Provided the Reynolds number† of the turbulence is large enough, the rate of transfer of energy from the large to the small eddies is identical with the total rate of dissipation of energy by viscosity ; hence the second relevant parameter is ϵ, the average rate of dissipation per unit mass of fluid. No other parameters seem to have an influence on the small eddies, and so we have Kolmogoroff's first similarity hypothesis :

" The average properties of the small-scale components of *any* turbulent motion with large Reynolds number are determined uniquely by the quantities ν and ϵ."

The usefulness of this hypothesis lies in its applicability to all kinds of turbulent motion, irrespective of the origin of the turbulence and of the distribution of mean velocity. We need, of course, to specify more closely what is meant by the small-scale structure of the motion. This is difficult, although it will always be true that there are some sufficiently small components of the turbulence to which the theory applies. The larger the Reynolds number of the motion, the greater will be the range of eddy sizes included within the scope of the hypothesis. In general

* The author promises that this is the last time he will quote this rhyme.

† Defined by, say, $E^{1/2}L/\nu$, where E is the average energy of the turbulence per unit mass of fluid and L is a length representative of the eddies containing most of the turbulent energy.

the theory will not apply to eddies which are large enough to fall within regions of the spectrum containing an appreciable proportion of the total turbulent energy, for these will normally be subject to direct large-scale influences, such as the boundary conditions of the flow. Thus in turbulence in a wind-tunnel stream the energy-containing region of the spectrum is excluded from the theory because this region is directly influenced by the fact that the turbulence is decaying. In a pipe, some, if not all, of this same region of the spectrum is excluded because it is directly influenced by the conversion of mean pressure energy into energy of turbulence. It is only the tail end of the spectrum to which Kolmogoroff's similarity hypothesis applies.

The second similarity hypothesis depends even more directly on the assumption of very large Reynolds numbers of the turbulence. As the Reynolds number increases, smaller and smaller eddies are brought into existence and the region of the spectrum in which most of the viscous dissipation occurs shifts in the direction of smaller eddies. If this process goes far enough, the larger eddies of the range described by the first similarity hypothesis will contribute very little to the viscous dissipation ; that is, they are dominated by inertia forces and are little affected by variations in the viscosity ν, and we are led to the second of Kolmogoroff's similarity hypotheses :

" At sufficiently large Reynolds numbers of the turbulence there is an inertial subrange (at the large-eddy end of the range of small eddies mentioned in the first similarity hypothesis) in which the average properties are determined uniquely by the quantity ϵ."

To make analytical use of these two hypotheses in a discussion of some mean value related to the turbulence, it is necessary first to decide (usually on intuitive grounds) whether or not this mean value is influenced very strongly by the small-scale components of the motion. If it is not, the similarity theory can say nothing about it. If it is we deduce immediately that the mean value is a universal function of ϵ and ν and of any length or time variables involved in the definition of the mean value. From this stage on, it is wholly a matter of dimensional analysis.

As a simple example, consider $\overline{[u(\mathbf{x}+\mathbf{r})-u(\mathbf{x})]^2}$, where $u(\mathbf{x})$ and $u(\mathbf{x}+\mathbf{r})$ are the fluctuations in one component of the velocity at two points in space having position vectors $\mathbf{x}$ and $(\mathbf{x}+\mathbf{r})$ respectively. It seems reasonable to suppose that when r (the magnitude of $\mathbf{r}$) is small enough the larger eddies make very little contribution to the velocity difference, so that this mean value is determined almost wholly by eddies whose diameters are of the same or smaller order than r, and we are led to apply the similarity hypotheses. The dependence of the mean value on $\mathbf{r}$ is much more critical than that on $\mathbf{x}$ (*i.e.* for the smaller eddies, the turbulence is approximately homogeneous in space) and we infer that it is a universal function of the variables $\mathbf{r}$, ν and ϵ only. Dimensional reasoning then shows that

$$\overline{[u(\mathbf{x}+\mathbf{r})-u(\mathbf{x})]^2} = (\epsilon\nu)^{\frac{1}{2}} E\left(\frac{r\epsilon^{\frac{1}{4}}}{\nu^{\frac{3}{4}}}\right)$$

where E is a universal function of its vector argument. The continuity conditions

and the fact that the small eddies are isotropic then determine the dependence of E on the direction of the vector $\mathbf{r}$, and we have (Batchelor, 1947) finally

$$\overline{[u(\mathbf{x}+\mathbf{r})-u(\mathbf{x})]^2} = (\epsilon\nu)^{\frac{1}{2}}\left(F + \frac{r_1^2}{2r}\frac{dF}{dr}\right) \quad . \quad . \quad (2.1)$$

where r_1 is the component of $\mathbf{r}$ in the direction of u and F is a universal function of the scalar argument $\frac{r\epsilon^{\frac{1}{4}}}{\nu^{\frac{3}{4}}}$.

This is as far as we can go with the aid of the first similarity hypothesis. Now it seems reasonable to suppose that eddies which are much smaller than r will contain too little energy to make an appreciable contribution to $\overline{[u(\mathbf{x}+\mathbf{r})-u(\mathbf{x})]^2}$ (over the whole of the "Kolmogoroff range" the energy falls off rapidly with decrease of the eddy size). Hence this mean value is chiefly determined by eddy sizes in the neighbourhood of r and there is the possibility of using the second similarity hypothesis when the Reynolds number is large. Provided r is suitably limited both above and below, *viz.* provided r is much less than the sizes of the energy-containing eddies and provided r is much greater than the length $\left(\frac{\nu^3}{\epsilon}\right)^{\frac{1}{4}}$ which is representative of the region of influence of viscosity, the function F in (2·1) must have a form such that ν disappears from the whole expression. This requires that $F = c_1\left(\frac{r\epsilon^{\frac{1}{4}}}{\nu^{\frac{3}{4}}}\right)^{\frac{2}{3}}$, where c_1 is an absolute constant, so that

$$\overline{[u(\mathbf{x}+\mathbf{r})-u(\mathbf{x})]^2} = c_1(\epsilon r)^{\frac{2}{3}}\left(1 + \tfrac{1}{3}\frac{r_1^2}{r^2}\right) \quad . \quad . \quad (2.2)$$

for r within the range specified.

The evidence available from wind tunnel measurements (see papers in the course of preparation) is consistent with the prediction that the relation (2.2) becomes accurate at large enough* Reynolds numbers. Predictions about the energy spectrum function are even more definite, because the level of the spectrum at any given wave-length is determined by a narrower range of eddy sizes than are correlation functions like $\overline{[u(\mathbf{x}+\mathbf{r})-u(\mathbf{x})]^2}$. A correlation function has been chosen as an example here since the quantities which are measured in atmospheric turbulence will usually be of the correlation function type. The arguments to be used in any application of the similarity theory to atmospheric turbulence will be closely similar to that outlined above.

3. The applicability of the similarity hypotheses to the turbulence in the atmosphere and ocean

The first and most immediate requirement for the application of the similarity hypothesis is that a state of turbulent motion should exist. We need not be very

* The lower limit of the Reynolds number $E^{1/3}L/\nu$ for validity of (2.2) is not yet known accurately, but it is unlikely to be above 5×10^4, which is less than the Reynolds numbers of the turbulent motions likely to be found in the atmosphere and ocean.

precise about what we mean by turbulence ; it is sufficient to look for random fluctuations of any property of the medium which are smaller in size and period than the variations generated directly by the boundary conditions of the motion. It will normally be easy to decide whether this requirement is satisfied, although difficulties may arise when the observations are meagre. Many relevant observations are already available. So far as the author can ascertain from the meteorological literature, there is considerable uncertainty about the source of energy of velocity fluctuations which are observed in the atmosphere outside the friction layer of the earth's surface, but at least it is firmly established that in general velocity fluctuations *do* occur. These fluctuations have small enough length and time scales* to obey statistical laws, and there does not appear to be any reason to doubt that they are part of a turbulent motion. Within the surface friction layer there are of course many observations, as well as strong theoretical expectations, to show that there exists a state of fully-developed turbulence (*i.e.* a turbulent motion determined chiefly by the local conditions). As for the ocean, the number of observations made at positions away from the surface seems to be very small and it is difficult to draw firm conclusions. If, as seems not unlikely, there is a strongly stable distribution of density over most of the ocean depth, this density distribution might prevent the establishment of a turbulent motion by large-scale currents. In shallow water and in the presence of currents there will normally be fully-developed turbulence.

A second requirement is that the range of eddy sizes over which it is intended to apply the similarity hypotheses should be free from external influences. The physical idea behind the hypotheses is that of a statistical balance or equilibrium of the smaller eddies, the only source of energy for this range being the transfer of energy from larger eddies. Clearly, if there is some external influence feeding energy directly into some part of the range of small eddies, the balance will not have the assumed universal form and the hypotheses will not be applicable. If there is some influence supplying energy to turbulent eddies with diameters in the neighbourhood of d (as, for example, a layer of depth d of unstable density gradient in the atmosphere), we can expect the similarity hypotheses to be applicable only to eddies considerably smaller than d. In other words the statistical decoupling must be given a chance to eliminate the external influence.

In brief, we must know first that a turbulent motion is present and second that the eddies to which we intend to apply the similarity hypotheses are small compared with any which are subject to direct external influences. In wind tunnel work it would be safe to say simply that we must apply the hypotheses only to eddies which are small compared with those containing most of the energy of the turbulence, because the possibility that some external agency is influencing the energy spectrum exists, in general, only for the larger energy-containing eddies. But we must be more cautious in the atmosphere and ocean. The range of eddy sizes is here so enormous, and the number of external influences so large, that the possibility of

* See, for instance, the evidence provided by Fig. 1 (b) in the paper by Priestley and Swinbank (*Proc. Roy. Soc.*, London, A, **189**, p. 543).

direct interference in what would otherwise be a universal statistical balance can never be excluded. When such interference does occur, then the similarity hypotheses will apply only to eddies which are much smaller than the eddies subject to the interference. Each particular case should be examined on its merits with the above requirements in mind.

Owing to the very large size of the energy-containing eddies in the atmosphere and the very small magnitude of the length $\left(\frac{\nu^3}{\epsilon}\right)^{\frac{1}{4}}$ which is representative of the region of influence of viscosity, the inertial subrange of eddy sizes is extremely large in the atmosphere. One hesitates to estimate the size of the main energy-containing eddies in the atmosphere, but in order to attract better estimates from those familiar with the evidence I should say that, judging by the movement of wisps of cloud as seen from an aeroplane, it will be at least of the order of 100 m. at stations far from the ground. The quantity $\left(\frac{\nu^3}{\epsilon}\right)^{\frac{1}{4}}$ can be determined with a little more confidence. The average energy dissipation per unit mass throughout the lowest 10 km of the atmosphere has been estimated by Brunt (*Dynamical Meteorology*, 2nd Ed., p. 286) to be of the order of 5 $cm^2\ sec^{-3}$ and on taking ν to about 0.15 $cm^2\ sec^{-1}$ in the lower layers of the atmosphere, we find

$$\left(\frac{\nu^3}{\epsilon}\right)^{\frac{1}{4}} = 0{\cdot}2 \text{ cm}^*.$$

Thus apart from the possibility of external influences, the range of eddy sizes over which the second of Kolmogoroff's similarity hypotheses is applicable is very large. This is an advantage of considerable value because of the extreme simplicity of conditions in the inertial subrange.

Having satisfied ourselves that there will certainly be some occasions on which the similarity hypotheses are applicable to atmospheric and oceanic turbulence, we now consider what can be learnt from the theory. There are all the predictions of the kind represented by Eqs. (2.1) and (2.2), and details can be found in the literature (Batchelor 1948). Most of these predictions are concerned with quantities which are of particular interest in connexion with decaying turbulence, flow in pipes, turbulent wakes, *etc.* In this paper we want, on the other hand, to consider predictions about quantities which are of practical importance in meteorology and oceanography. The problem of the diffusion of smoke or water-vapour or other non-dynamical qualities† immediately springs to mind, and is the one chosen for consideration below. The possibility of other new applications of the similarity hypotheses will probably occur to meteorologists.

4. Diffusion from a fixed source

There are two fairly distinct types of problem of turbulent diffusion. The first is diffusion from a fixed emitting source (Batchelor 1948) and the second is

* Only the order of magnitude of this representative length is significant.

† That is, qualities which confer no new dynamical properties on the fluid elements which act as carriers of the qualities.

the diffusion of a discrete cloud which follows the motion of the fluid (Batchelor, to be published). The first problem is the simpler, and requires a kind of analysis which is Eulerian in the sense that one enquires into the probable concentration of the diffusing substance at various points relative to the fixed source. It is found that this kind of analysis involves the correlation between the velocities of a single fluid particle at two different instants. The second problem involves analysis which is Lagrangian in the sense that we are concerned with the distribution of probable concentration relative to a centre which moves with the fluid. This kind of analysis involves correlations between the velocities of two different fluid particles at different instants. Some analysis of these two problems will be found in the two papers cited ; only the question of the use of the similarity hypotheses is to be considered here.

Consider first the fixed source problem. The distribution of probable concentration of diffusing substance about the source is known when the statistical behaviour of one fluid particle initially situated at the source is known. By far the most important statistical quantity is the mean dispersion, or mean square displacement of the particle from the source, after a time t. Hence, with the similarity hypotheses in mind, we ask if this mean dispersion is strongly dependent on the smaller eddies of the turbulence for any value of t.

Now G. I. Taylor (1921) has pointed out that if $X(t)$ and $u(t)$ are the projections on the x-axis of the displacement and velocity of any fluid particle t seconds after leaving the source, the rate of increase of the mean dispersion is

$$\frac{d\,\overline{X^2(t)}}{dt} = 2\,\overline{X(t)\,u(t)} = 2\int_0^t \overline{u(t')\,u(t)}\,dt'.$$

The dependence of the correlation $\overline{u(t')\,u(t)}$ on $(t-t')$ will always be much stronger than the dependence on either t or t' separately, so that we can write $\overline{u(t')\,u(t)} = S(t-t')$ and

$$\frac{d\,\overline{X^2(t)}}{dt} = 2\int_0^t S(\xi)\,d\xi$$

Hence it is necessary to decide whether $S(\xi)$ is strongly influenced by the small eddies. When $\xi = 0$, $S(\xi)$ reduces to $\overline{u^2}$, which is the aggregate of energy of eddies of all sizes and will certainly not be strongly dependent on the small eddies. When ξ increases from zero, the effect on $S(\xi)$ is to weight more strongly the slower eddies of the motion, *i.e.* those to which the similarity theory does not apply. The conclusion is that for no value of t is $\frac{d\,\overline{X^2(t)}}{dt}$ strongly influenced by the small eddies and that the similarity hypotheses cannot be applied to this quantity.

A limitation of the averaging process seems to offer the possibility of obtaining a quantity which is determined by the small eddies. For instance, in the case of a time average of the diffusion from a continuously emitting source, a natural suggestion is to use a limited averaging time and to regard the turbulent fluctuations as consisting only of the deviations from the appropriate average over this limited

time. In this way the effect of the big eddies appears to have been separated out as a mean motion, leaving fluctuations controlled by the small eddies. However the conditions of validity of this separation of the effects of large and small eddies are not apparent, and the whole question has yet to be made the subject of a proper mathematical investigation.

The tentative conclusion, then, is that the similarity hypotheses cannot be applied to the fixed-source type of diffusion problem.

5. Diffusion from a moving centre

Here we are concerned with a cloud of fluid particles which are marked in some way (*e.g.* by smoke). The cloud changes its shape as it follows the motion of the fluid and the diffusion will be measured by the average, over a large number of releases of exactly similar clouds, of the rate of change of geometrical properties of the cloud. Just as the fixed source problem can be reduced to a discussion of the statistical behaviour of *one* particle leaving the source, so the most important features of the moving centre problem can be reduced to a discussion of the statistical relative behaviour of *two* fluid particles. The second of these two particles is a moving origin replacing the fixed origin of the former problem.

Suppose that the two chosen particles are initially separated by a vector $\mathbf{l}_0$ (with components ξ_0, η_0, ζ_0 and magnitude l_0) and that as a result of the turbulence the separation for any one trial is $\mathbf{l}\,(t)$ (components $\xi(t)$, $\eta(t)$, $\zeta(t)$ and magnitude $l(t)$, at a time t seconds later. Let $\delta u(t)$ be the x-component of the relative velocity of the two particles t seconds after the instant of release. If a large number of pairs with initial separation $\mathbf{l}_0$ is released, the rate of increase of average dispersion of the two particles in the x-direction at time t is

$$\frac{d\,\overline{\xi^2(t)}}{dt} = 2\,\overline{\xi(t)\;\delta u(t)} = 2\,\overline{\left[\xi_0 + \int_0^t \delta u(t')\;dt'\right]\;\delta u(t)}$$
$$= 2\int_0^t \overline{\delta u(t)\;\delta u(t')}\;dt' \quad . \quad . \quad . \quad . \quad (5.1)$$

since ξ_0 is the same for all the pairs of particles over which the average is taken.

We are immediately encouraged in the belief that the similarity hypotheses are applicable to the quantity $\dfrac{d\,\overline{\xi^2(t)}}{dt}$ for at least some values of t because of the occurrence of velocity *differences* in the integrand of Eq. (5.1). When t is sufficiently small $\delta u(t')$ is approximately constant (and equal to $\delta u\,(0)$) over the range of integration and Eq. (5.1) reduces to

$$\frac{d\,\overline{\xi^2(t)}}{dt} \approx 2t\,\overline{\delta u^2(0)} = 2t\,\overline{[u(\mathbf{x}) + \mathbf{l}_0) - u(\mathbf{x})]^2}, \quad . \quad . \quad . \quad (5.2)$$

which has already been seen to be determined chiefly by the small eddies when l_0 is sufficiently small. On the other hand, when t is very large, the two particles are far apart and the relative velocity between them will be controlled by the large eddies ; in fact ultimately

$$\frac{d\,\overline{\xi^2(t)}}{dt} \longrightarrow 2\,\frac{d\,\overline{X^2(t)}}{dt}$$

because the two particles wander independently. Roughly speaking, the relative velocities in the integrand of (5.1) will depend strongly on the small-scale components of the turbulence provided the distance between the particles is not greater than the diameters of these small eddies, *i.e.* provided l_0 and t are not too large.

Thus the similarity hypotheses are applicable to $\frac{d\,\overline{\xi^2(t)}}{dt}$ for a limited range of values of l_0 and t. Within this range we infer that $\frac{d\,\overline{\xi^2(t)}}{dt}$ is a universal function of the parameters ν, ϵ and the variables t and $\mathbf{l}_0$*. Dimensional arguments then show that

$$\frac{d\,\overline{\xi^2(t)}}{dt} = \nu\, G\left(\frac{\mathbf{l}_0\epsilon^{\frac{1}{4}}}{\nu^{\frac{3}{4}}}\,,\ \frac{t\epsilon^{\frac{1}{2}}}{\nu^{\frac{1}{2}}}\right) \quad . \quad . \quad . \quad . \quad . \quad (5.3)$$

where G is a universal function of two variables. The prediction can be made more specific by considering some special cases. In the first place we can consider the case in which t is so small that, as pointed out above, $\frac{d\,\overline{\xi^2(t)}}{dt}$ is linear in t and has a form given by Eqs. (5.1) and (2.1). Second, when l_0 is suitably restricted above and below, as explained in section 2, so that inertia forces dominate the relative motion of the two particles to the exclusion of the effect of viscosity, G must have a form such that ν does not occur in the expression (5.3). The result for the combined case of small t and l_0 in the inertial subrange is given by Eqs. (1.5)

TABLE I. EXPRESSIONS FOR $\frac{d\,\overline{\xi^2(t)}}{dt}$

Restrictions on l_0 / Restrictions on t	General case (excluding l_0 large)	l_0 in inertial subrange
General case (excluding t large)	$\nu\, G\left(\frac{l_0\epsilon^{\frac{1}{4}}}{\nu^{\frac{3}{4}}}\,,\ \frac{t\epsilon^{\frac{1}{2}}}{\nu^{\frac{1}{2}}}\right)$	$t^3\,\epsilon\, G_1\left(\frac{l_0}{\epsilon^{\frac{1}{2}}\,t^{\frac{3}{2}}}\right)$
t small	$2\,t\,(\epsilon\,\nu)^{\frac{1}{2}}\left(F + \frac{\xi_0^{\,2}}{2l_0}\frac{dF}{dl_0}\right)$ $F \equiv F\left(\frac{l_0\epsilon^{\frac{1}{4}}}{\nu^{\frac{3}{4}}}\right)$	$2\,c_1\,t\,(\epsilon\,l_0)^{\frac{2}{3}}\left(1 + \frac{1}{3}\frac{\xi_0^{\,2}}{l_0^{\,2}}\right)$
t intermediate	$\nu\, G_2\left(\frac{t\epsilon^{\frac{1}{2}}}{\nu^{\frac{1}{2}}}\right)$	$c_2\,\epsilon\,t^2$

* The relevant variable is the total vector joining the two particles and not the projection on any axis, since the former quantity determines the size of the dominant eddies. Owing to the isotropy of the small eddies the speed of the diffusion in any direction is of the same order of magnitude for all directions of $\mathbf{l}_0$. The only effect of alteration of the direction of $\mathbf{l}_0$ will be to vary the numerical constants, as already seen in Eq. (2.2.).

and (2.2). All these special cases are exhibited in the table. G_1, G_2, are new universal functions, and c_1, c_2, are universal constants of order of magnitude unity.

Yet another special case may be considered. When t is so large that the particles are far apart and $\overline{\xi^2(t)} >> l_0^2$, the dependence of the diffusion on l_0 will be weak. After a long time the rate of spreading will be approximately independent of the way in which the particles were released. Provided that the particles are not yet far enough apart for the diffusion to be affected by the energy-containing eddies, there will thus be a range of values of t (to be called " intermediate " values) for which the function G in Eq. (5.3) must depend only on $\frac{t\epsilon^{\frac{1}{2}}}{\nu^{\frac{1}{2}}}$. This leads to the results shown in the last row of the table.

It was pointed out earlier that the inertial subrange of eddy sizes is exceedingly large in the free atmosphere, extending from a length large compared with 0·2 cm (say, about a metre) to an undetermined upper limit (L, say) which can scarcely be less than 100 m. Thus diffusion experiments of the kind described above, when carried out in the atmosphere, will in all probability employ values of l_0 in the inertial subrange. The simple results of the last column of the table therefore have a wide field of application.

The time (t_1, say) which marks the division between " small " and " intermediate " values of t is a parameter of the similarity range of eddies and will therefore be determined by ϵ and l_0 alone (ignoring ν, as is appropriate in the atmosphere). That is,

$$t_1 = \alpha\, l_0^{\frac{2}{3}}\, \epsilon^{-\frac{1}{3}} \quad . \quad . \quad . \quad . \quad . \quad (5.4)$$

where α is an absolute constant of order unity. The predictions which are important for the atmosphere can thus be written

$$\frac{d\,\overline{\xi^2(t)}}{dt} = t^2 \epsilon\, G_1\left(\frac{l_0}{\epsilon^{\frac{1}{2}} t^{\frac{3}{2}}}\right) \begin{cases} = 2\, c_1\, t\, (\epsilon\, l_0)^{\frac{2}{3}} \left(1 + \frac{1}{3}\frac{\xi_0^2}{l_0^2}\right) & \text{for } t << l_0^{\frac{2}{3}}\, \epsilon^{-\frac{1}{3}} \quad . \quad . \quad (5.5) \\ = c_2\, \epsilon\, t^2 & \text{for } t >> l_0^{\frac{2}{3}}\, \epsilon^{-\frac{1}{3}} \quad . \quad . \quad (5.6) \end{cases}$$

provided in both cases that $\overline{\xi^2(t)} << L^2$, and, at the other extreme,

$$\frac{d\,\overline{\xi^2(t)}}{dt} \longrightarrow 2\,\frac{d\,\overline{X^2(t)}}{dt} \quad \text{as } t \longrightarrow \infty .$$

The results for small and intermediate values of t may be combined by a simple approximate interpolation formula, *viz.*

$$\frac{d\,\overline{\xi^2(t)}}{dt} = 2\, C_1\, (\epsilon\, l_0)^{\frac{2}{3}} \left(1 + \frac{1}{3}\frac{\xi_0^2}{l_0^2}\right) + C_2\, \epsilon\, t^2 \quad . \quad . \quad (5.7)$$

which will be valid provided $\overline{\xi^2(t)} << L^2$. The integrated expression for $\overline{\xi^2(t)}$ is

$$\frac{\overline{\xi^2(t)} - \xi_0^2}{l_0^2} = c_1 \left(\frac{t\,\epsilon^{\frac{1}{3}}}{l_0^{\frac{2}{3}}}\right)^2 \left(1 + \frac{1}{3}\frac{\xi_0^2}{l_0^2}\right) + \frac{1}{3}\, c_2 \left(\frac{t\,\epsilon^{\frac{1}{3}}}{l_0^{\frac{2}{3}}}\right)^3 \quad . \quad . \quad (5.8)$$

Similar formulae for $\overline{\eta^2(t)}$ and $\overline{\zeta^2(t)}$ will apply with the same values of the constants

c_1 and c_2 so that the mean square distance between the particles varies according to

$$\frac{\overline{l^2(t)} - l_0^2}{l_0^2} = \frac{10}{3} c_1 \left(\frac{t\epsilon^{\frac{1}{3}}}{l_0^{\frac{2}{3}}}\right)^2 + c_2 \left(\frac{t\epsilon^{\frac{1}{3}}}{l_0^{\frac{2}{3}}}\right)^3 \quad . \quad . \quad . \quad (5.9)$$

A simple prediction, which offers the possibility of an experimental check, is that

$$\overline{\xi^2(t)} - \xi_0^2 = \frac{4}{3}\overline{\eta^2(t)} = \frac{4}{3}\overline{\zeta^2(t)} \quad . \quad . \quad . \quad . \quad . \quad (5.10)$$

when t is " small " and in the special case when $\mathbf{l}_0$ is parallel to the x-axis.

It will be noticed that the so-called " small " and " intermediate " values of t are equivalently defined by $\frac{\overline{\xi^2(t)} - \xi_0^2}{l_0^2} << 1$ and $>> 1$ respectively. If the proportional change in separation of the particles is small compared with unity, t is " small," and correspondingly if the proportional change of separation is much greater than unity, we have the condition of intermediate values of t. It should therefore be easy to decide, when analysing some observations, which of the results of the similarity theory is appropriate.

The results given in this section apply directly to pairs of particles and with this information it is possible to give a partial description of the rate of change of shape of a continuous distribution of particles forming a cloud. Details of this extension will be found elsewhere (Batchelor, to be published).

6. Observations of diffusion in the atmosphere and ocean

Two sets of observations of the relative diffusion of pairs of particles have been published recently (Durst 1948, Richardson and Stommel 1948). In neither case was an application of the similarity hypotheses envisaged when the observations were made, but nevertheless they can now be considered for that purpose.

C. S. Durst (1948) has described observations of the relative motion of two small puffs of smoke at various heights in the atmosphere. The results are analysed by H. Charnock (unpublished), with the similarity theory in mind, and need not be discussed here. It appears that this is a case in which l_0 lies within the inertial subrange and in which t is " small."

A set of observations of the relative motion of pairs of small floats on the surface of Loch Long has been recorded by L. F. Richardson and H. Stommel (1948). The projection of the distance between the floats in a certain direction was measured at the beginning and end of an interval of 30 sec for several different pairs. The authors divide the pairs into two groups ; 23 " close " pairs with (projected) initial separations ranging from 0 to 52 cm and 22 " wide " pairs with initial separations ranging from 117 to 320 cm. Choosing the axis of projection as the x-axis and taking averages over all the pairs within each group, the authors state that

close pairs : $\frac{1}{2}\overline{[\xi_0 + \xi(t)]} = 26{\cdot}7$ cm, $\overline{[\xi(t) - \xi_0]^2} = 384$ cm^2,

wide pairs : 188 cm, 5058 cm^2,

and the power-law which fits these two points and passes through the origin is

$$\frac{\overline{[\xi(t) - \xi_0]^2}}{t} = 0{\cdot}14 \left[\frac{\overline{\xi(t) + \xi_0}}{2}\right]^{1{\cdot}4} \quad . \quad . \quad . \quad (6.1)$$

In a note added at the proof stage of the printing of their paper, Richardson and Stommel claim that the empirical relation (6.1) confirms the similarity theory as set out by Weizsäcker (1948). This appears to be a misunderstanding, as none of the predictions of the similarity theory have a form similar to (6.1). The prediction which bears the closest resemblance to (6.1) is the relation (5.6), which can be written in the form

$$\frac{d\,\overline{\xi^2(t)}}{dt} = (9c_1\epsilon)^{\frac{1}{3}}\,[\overline{\xi^2(t)}]^{\frac{2}{3}} \quad . \quad . \quad . \quad . \quad . \quad (6.2)$$

and which is valid when $t >> l_0^{\frac{2}{3}}\,\epsilon^{-\frac{1}{3}}$ and $\overline{\xi^2(t)} << L^2$. However even this prediction should not be compared with the observations, because (6.2) refers to "intermediate" values of t and values of $[\overline{\xi^2(t)} - \xi_0^2]/\xi_0^2$ which are $>> 1$, whereas the observations show that* $\overline{[\xi(t) - \xi_0]^2} \Big/ \left[\frac{\overline{\xi(t) + \xi_0}}{2}\right]^2 = 0{\cdot}58$ (close pairs) and $0{\cdot}12$ (wide pairs). These figures are neither large nor small compared with unity, but it would clearly be more correct to try to interpret the observations as a case in which t is "small" and in which the prediction (5.5) is appropriate. We then come up against the difficulty that only the projected distances between the particles were observed, and we have no means of determining the total distance l_0. In order to get a rough order-of-magnitude result we can overcome this difficulty by supposing that Richardson's and Stommel's observations are total distances and by comparing them with

$$\frac{l^2(t) - l_0^2}{t} = \tfrac{10}{3}\, c_1 t(\epsilon l_0)^{\frac{2}{3}}.$$

The observed variation with l_0 now disagrees with the theory, of course. By considering each group of observations in turn we find that the close pairs lead to $\epsilon = 0{\cdot}011 \left(\frac{3}{10\,c_1}\right)^{\frac{3}{2}}$ cm^2 sec^{-3}, and the wide pairs to $0{\cdot}071\ (0{\cdot}3/c_1)^{\frac{3}{2}}$ cm^2 sec^{-3}. These figures (taking C_1 as being of order unity) are roughly of the right order of magnitude for the conditions of Loch Long, *i.e.* for an open stretch of water two metres deep and with a slight tidal current flowing. For comparison we may note G. I. Taylor's (1919) computation that the average rate of dissipation of kinetic energy per unit mass of fluid over a year in the Irish Sea is about $0{\cdot}080$ cm^2 sec^{-3}.

In an earlier paper, Richardson (1926) has discussed the available data concerning the variation of turbulent diffusion coefficients (of all kinds) with the size l

* Note that for an average over a large number of trials with the same value of $\mathbf{l}_0$,

$$\overline{[\xi(t) - \xi_0]^2} = \overline{\xi^2(t)} + \xi_0^2 - 2\,\xi_0\,[\xi_0 + \overline{\textstyle\int_0^t \delta u\,(t')\,dt'}] = \overline{\xi^2}(t) - \xi_0^2$$

and

$$\tfrac{1}{2}\,[\overline{\xi(t) + \xi_0}] = \xi_0$$

of the region over which the observations were made. He finds that the diffusion coefficient K varies roughly according to

$$K = 0{\cdot}2\ l^{4/3} \quad . \quad . \quad . \quad . \quad . \quad (6.3)$$

for five groups of observations ranging in scale from $l = 1{\cdot}5 \times 10^3$ cm to $l = 5 \times 10^6$ cm. Even though the observations were fairly crude and the definition of the diffusion coefficients varied, it is probable that there is a link between this result and the similarity theory. The first two (Schmidt and Akerblom) of the groups of observations mentioned were of the wind profile at different distances from the ground and consequently the diffusion coefficient obtained from these observations is a coefficient of vertical transfer (of momentum). The third group (Taylor) concerned observations of the rate at which changes in conditions at the sea surface are propagated through the lowest 500 m of the atmosphere and also gave a coefficient of vertical transfer (of heat). Now since these three groups of observations concern vertical transfer in the neighbourhood of a horizontal boundary, it is clear that eddies which are large compared with the distance of the measuring point from the ground will have little effect on the transfer. Hence, the computed diffusion coefficients are determined chiefly by eddies comparable or smaller than the distance from the ground and in a rough way come within the scope of the similarity theory. The other two groups concerned observations of the scatter of various diffusing particles (balloons in one case, volcano ash in the other) about their mean position some time after their release. The process of computing scatter about a mean position effectively eliminates most of the effect of large eddies*, which displace the group as a whole, and the resulting diffusion coefficient is similar to the quantity $\frac{d}{dt}\overline{l^2(t)}$ which was discussed in section 5.

It is clear from the necessarily crude form of all five groups of observations that the conditions assumed by the similarity hypotheses do not apply rigorously, and there is no purpose served by enquiring into the exact relation between the different kinds of diffusion coefficient. Nevertheless in each case a quantity which weights the effect of eddies smaller than a certain size is obtained. In none of the observations is the instant of release of the diffusing particles an important parameter, and a relation of the form

$$K \propto \epsilon^{\frac{1}{3}} l_0^{\frac{4}{3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6.4)$$

is therefore predicted by the similarity theory (as already seen in Eq. (6.2)). The agreement between Eqs. (6.3) and (6.4) entitles us to claim that Richardson's empirical law is consistent with the similarity theory. Moreover using Brunt's estimate that $\epsilon = 5$ cm^2 sec^{-3} in the atmosphere, we find $\epsilon^{\frac{1}{3}} = 1{\cdot}7$ cm$^{\frac{2}{3}}$ sec^{-1}, which is of the order of magnitude of the numerical coefficient in (6.3) as expected on the similarity theory. The agreement has already been noticed by A. Obukhoff (1941).

* With the reservation noted in section 4.

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The climatic fluctuation since A.D. 1850 in Europe and the Atlantic

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Summary

Trend-curves of thirty-year means are discussed

(a) in general terms and then applied specifically to
(b) temperature,
(c) pressure,
(d) rainfall,
(e) wind,
(f) temperature gradient and
(g) temperature amplitude.

Correlations between the departures of the different elements suggest that we can consider the various anomalies as depending on those of pressure and wind. This is notably true of rainfall departures which can be regarded as the sum of two terms, the " area " term depending on the pressure anomaly and the " local " term depending on the vector wind anomaly. High pressure is associated not only with consistently dry years but also with cold years. Variations of wind or pressure gradient are particularly felt as changes of frequency of the prevailing wind. The southwesterly component is of course linked with the " zonal index " and the circulation of the wind systems of the earth. The increase of this component gives more maritime conditions and, except to the lee of hills or mountains, wetter weather. The recent increase explains the main differences between nineteenth and twentieth century climates but not the phases of the transition. These phases necessitate first the concept of a ring of high pressure which, by some south-steering process, left the Arctic Circle about 1880 and reached the Tropic of Cancer about 1915. Preceding and following this ring are rings of high rainfall, low pressure and high temperature-gradient that can be loosely regarded as frontal belts. At any one place therefore, the following sequence of five phases should occur : the first front (Frontal-A stage), the easterly or cold period (T-min), the pressure maximum (P-max), the westerly period culminating in the second front (Frontal-B stage).

In the British Isles the five phases explain the climatic fluctuations from 1875 to 1925 and much of the same sequence can be followed in Scandinavia from 1865 to 1915, Italy from 1885 to 1935 and in the United States from 1895 to 1945. Temperature data suggest that this equatorward movement with time may be of more general application, and that the preceding West European climatic fluctuations can also be interpreted as anomaly patterns which spread from the north to the south.

Pressure anomalies are normally greater over oceans than continents. The south-steering of anomaly patterns necessitates, therefore, a backing of the prevailing wind in NW. Europe after the pressure maximum (P-max) of about 1895. Such a change is confirmed by the wind records themselves.

An effect of persistent wind on ocean temperatures and therefore pressures might well account for the south-steering, but there is as yet no evidence that delayed action effects of this kind occur.

1. Introduction

Thirty year means have come to be regarded with special significance ; means for the period 1901-30, following the recommendation of the International Climatological Commission, are often used as " normals." Curves of overlapping thirty-year means are used to indicate trends, and differences between two such means measure, by definition, " fluctuations " (see Ahlmann 1948/9, p. 165). This present

paper deals only with climatic anomalies sufficiently persistent to be termed "fluctuations"; it is therefore convenient to express any thirty-year period in terms of its fifteenth year and the convention adopted will be :—

1841-70 = *c. 1855*

1851-80 = *c. 1865, et. seq.*

For simplicity the data used (*e.g.* in Figs. 1 to 6 and in Table X) were calculated for ten-year *intervals* in this manner; the main conclusions apply *a fortiori* to charts of overlapping thirty-year means (available in Hesselberg-Birkeland 1943, Labrijn 1945, Ahlmann 1948/49, *etc.*); curves of either kind will be denoted below as "trend-curves" and form material relevant to this paper. Lysgaard's (1950) work appeared after this paper was set up in print, but it may now be regarded as the standard work of reference throughout.

2. Trend-curves

(a) *Procedure*

The measurement of climatic fluctuations necessitates approximate homogeneity, and the changes of basis for the data used below are less than

0·2°C (Temperature)

0·2 mb (Pressure)

2% (Rainfall)

The trend curves and maps (Figs, 1, 2, 3, 4 and 6) are independent of both units and normals, but, to express departures numerically, some choice must be made. The use of the standard period 1901-30 leads to such an excess of negative departures (in two of the three elements mentioned above) for Northern Europe that, wherever possible, the half-century 1851-1900 has been used instead.

(b) *Temperature*

Temperature trend-curves for widely-separated regions are almost identical. This similarity is particularly well-marked in the west-east direction (*cf.* Callendar 1938b, p. 655); the curve for New York State is nearly parallel to that for North-West Europe (*cf.* Callendar 1938a, p. 233). On the other hand, there is a considerable difference between curves for the Arctic Circle and the Mediterranean (see Fig. 1).

Departures from 1851-1900 normals are small in the eighteenth and nineteenth centuries. The recent rise of temperature appears first in the Iceland (Stykkisholm) trend-curve *c. 1873* and in South Scandinavia *c. 1878* (*cf.* Hesselberg-Birkeland 1943, Table IV and below, Fig. 1, curve a). In South England the change does not take place until about 1895 (*cf.* Fig. 1, curve c) and in SE. Europe not until 1905.

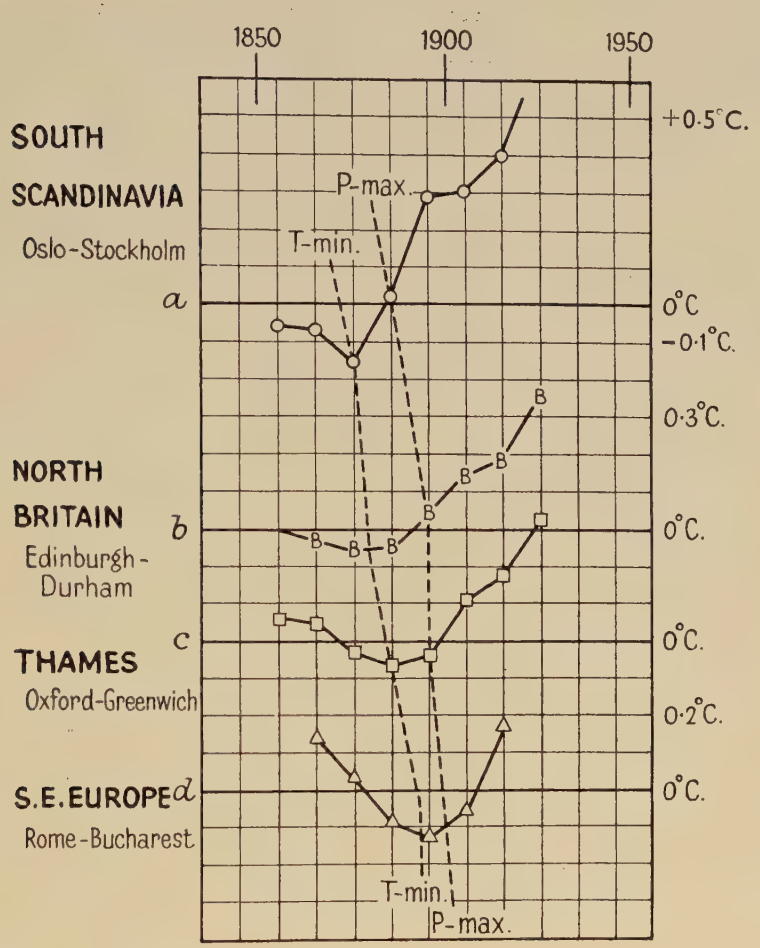

Figure 1. Temperature trend-curves for Europe, North to South, relative to 1851/1900 normals.

(c) *Pressure*

A valuable series of trend-curves was prepared by Hesselberg and Birkeland (1943 see especially p. 14, Fig. 5) for Northern and Atlantic Europe. However, the British data used by them, like many other annual means given in World Weather Records, are not sufficiently homogeneous to use for trend-curves and typical selections from various unpublished series have been used in Fig. 2.

The 2 mb increase of pressure gradient between Iceland and the Azores since *c. 1865* does in a general way account for the major differences between nineteenth

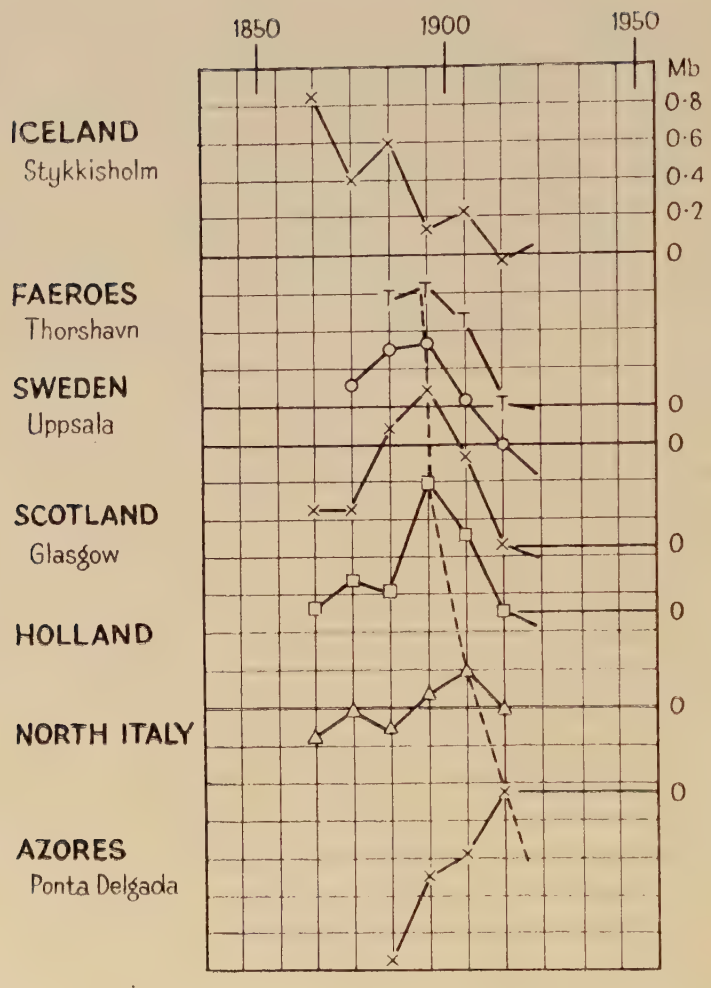

Figure 2. Pressure trends, Europe, North to South, relative to 1901/30 normals.

and twentieth century climate. These differences are summed up in a change of type from continental to maritime. This change has been elaborated elsewhere and it is with the more subtle phases of the transition that I now propose to deal.

Examination of individual pressure curves shows that the pressure maximum noticeable in Iceland in the period *c. 1865* and (Table IV) in parts of Norway *c. 1885 progressed* southwards, affecting the British Isles and Mid-Europe *c. 1895* and South Europe about *c. 1905* (Table V) and appears to have passed the Azores *c. 1920*. This period of 30 years of highest pressure is the fundamental concept of this paper and will be henceforth referred to as the P-max time.

(d) *Rainfall*

Rainfall trend-curves differ from those for temperature and pressure in one important respect. Curves for different parts of Scotland (Goldie and Carter 1939) and even for different parts of the Manchester-Chester area (*cf.* Boyd 1937) often have very different characteristics. This prevents the application of consistency tests ; attempts have been made to assess the homogeneity of long series on mathematical grounds (notably by O. V. Johannsson 1937). The general impression is that, at least after 1850, rainfall records are very reliable.

Comparative study of rainfall curves in different countries reveals a striking number of curves which are either parallel or inverse. Considering first the majority of nearly parallel curves, a well-marked dry period can be discerned, a period here called the R-min time. In North and East Europe this often occurs (Table IV) between *c. 1875* and *c. 1885*, in the British Isles in *c. 1895* and in the South Mediterranean in the present century. Between *c. 1895* and *c. 1925* regions north of 45°N. have become wetter and regions to the south drier. Lysgaard's (1948) world map of the rainfall difference between these two periods shows that this rule applies fairly generally from 80°W. to 50°E. The coincidence between the recent droughts in low latitudes and the warming of the Arctic has provided evidence for the growing belief that, conversely, ice ages are associated with pluvial periods in the tropics (*cf.* Brooks 1949, p. 95, or Ahlmann 1948/49, pp. 184-185). However, for our present purpose it is sufficient to notice that the R-min time has travelled southwards across Europe.

Some typical parallel curves for Western Europe are shown in Fig. 3 and these show that the R-min corresponds roughly with the P-max. The more interesting rainfall sites are however those which are sheltered only from the E or NE. (R-west sites) or only from the W. or SW. (R-east sites), and some of these have completely different trend-curves. R-west sites, such as West Central Lancashire (Boyd 1937), are usually wet when the circulation is strong. R-east sites on the other hand, such as Edinburgh, York or New England, are wet when the circulation is weak. The trend curves of R-west and R-east sites are respectively related directly and inversely to the excess or deficiency of SW. winds.

It will be demonstrated elsewhere that the parallel and inverse trends in rainfall are related to pressure and circulation effects respectively. More generally the following rule is applicable, at least to NW. Europe :—

The percentage departure of rainfall from any normal is the sum of two terms, the " area " or pressure term and the *" local " or wind term.* The area term is of the same sign and approximately the same amount over a large part of Europe and can be considered as proportional to the pressure departure. The local term is only partly due to chance and, over a long period, can be considered as dependent upon the vector departure of pressure gradient. The high pressure thus explains why the period 1881–1915 was dry in Britain ; the excess of east winds explains why " the period 1850–1890 was a rainfall minimum in many parts of Britain and the Continent, but in North-East Britain . . . was a rainfall maximum " (Schove 1949 b).

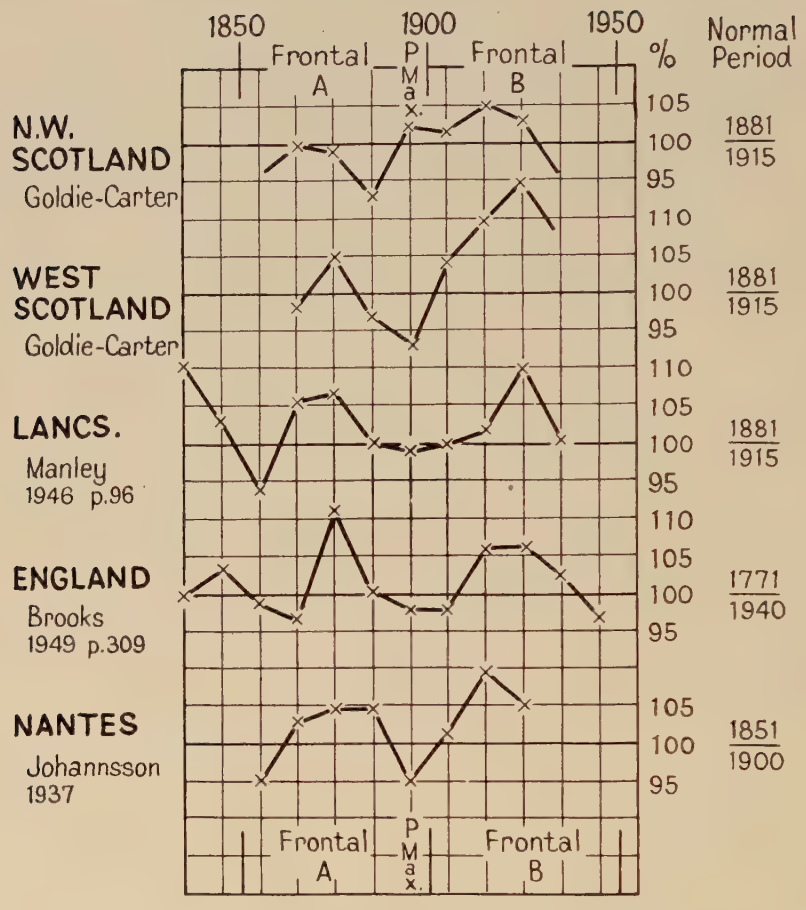

Figure 3. Rainfall by decades, W. Europe, North to South, relative to 1901/30 normals.

(e) *Pressure gradient (wind excess)*

Trend-curves of wind components can be compiled from frequency tables (*e.g.* Hesselberg–Birkeland 1943, Lysgaard 1949). However, the changes of basis in individual wind records can seldom be even specified, and, unless the curves are based on the means of at least two stations, no significance can be attached to variations of thirty-year means. However, the average results do correspond with the changes of pressure gradient. In England, both methods indicate (Table II) that the period *c. 1885* was a NE.'ly period and the period *c. 1915* a SW.'ly one. Pressure maps show that in North Italy both decades of the period 1891–1910 were NE.'ly and both decades of the period 1911–30 were SW.'ly (relative to the period 1901/30). It would appear therefore that wind anomalies affect England a few years before they affect North Italy (*cf.* Tables II and III).

(f) *Temperature gradient*

In synoptic meteorology a strong temperature gradient makes for persistence of type via fronto- and cyclo-genesis. A persistence of a frontal zone for a few weeks sometimes occurs (*cf.* Rossby 1950) ; in the winter of 1942 with the East Midlands snowbound and the West Midlands rainsoaked, would-be warm fronts were retarded by snow-cover and such a quasi-permanent frontal zone extended NNW.-SSE. across England.

Similar persistence, possibly for similar reasons, occurs over periods of years. In the 1870's there was (Table II) a tendency for such a frontal belt to lie NE.–SW. from South-East Scotland to South Ireland, an effect marked on pressure, temperature and rainfall maps for this notoriously wet decade. (*cf.* Glasspoole 1933, p. 256 and Dr. C. E. P. Brooks's remarks in discussion, p. 258). It will be shown below that this frontal belt moved slowly from north to south in the course of a half-century.

(g) *Temperature amplitude*

For 150 years the annual temperature amplitude has shown a progressive decrease associated with the change from dry continental to moist maritime conditions. The recent marked acceleration of this change appears to have begun about *c. 1870* between 55°N. and 60°N. (*cf.* Wagner 1928) and to have affected Central and Mediterranean Europe somewhat later. Winters have become much warmer, summers sometimes slightly cooler.

3. Some existing correlations

(a) *Pressure as an independent variable*

The various trend-patterns discussed above are not independent. High pressure and low rainfall are, except in the tropics, usually associated ; this association in fact holds not only for individual months or years but also for 30-year periods such as are at present under discussion.

High pressure and low temperature are in Europe positively correlated in winter months and it is the greater anomalies of the winter season that are largely reflected in the trend curves. The inverse relationship between the curves of Figs. 1 and 2 is striking. The T-min and P-max times do in fact almost synchronize.

The importance of pressure departures in interpreting seasonal and annual weather anomalies has been made clear by the methods of Sir Gilbert Walker, first in the Memoirs of the Indian Met. Dept. (*e.g.* Vol. **21**, 1915) and later in this country (*e.g.* Walker 1932). Recently Sandström (1941) and Brier (1947) have emphasized departures of both pressure and pressure gradient and the latter has published mean annual pressures for each latitude since 1899. The period is too short to justify the use of 30-year means but Brier has noted a decrease of pressure in northern high latitudes and it is assumed that this change is linked with the warming of the Arctic.

(b) *Pressure gradient as an independent variable*

It would be a convenient approximation to regard departures of any one meteorological element as dependent upon the departures of pressure and zonal index alone. However, in the present study it is more appropriate, especially for rainfall departures, to use as a *local* index of circulation the vector wind anomaly in the area concerned. For example, a SW. wind anomaly in the England area is usually associated with wet conditions at R-west sites such as West Lancashire and dry conditions at an R-east site such as York.

(c) *The P-max time*

Fig. 4 extends the results of Fig. 2 and shows in map form the varying dates at which the mean pressure for 30-years has been the highest since records began. It represents very neatly this southward progression, and suggests that the rule is of more general application. It should be noted however that discontinuities exist and that, owing to the lack of reliable records, it is not possible to present this map in the form of isochrones.

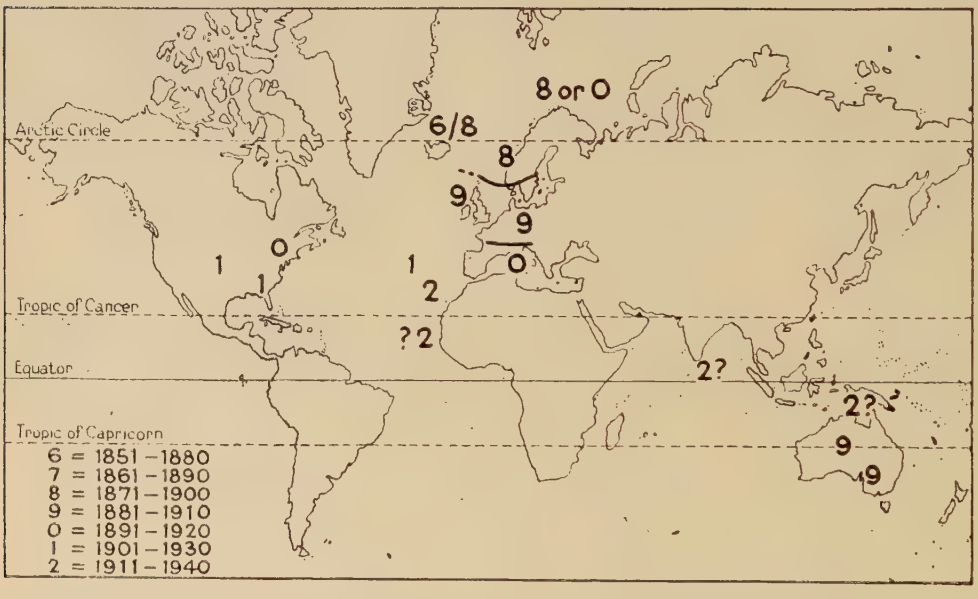

Figure 4. The P-max time : that 30-year period in which average pressure was the highest since records began.

(d) *The last T-min time*

Fig. 5 shows similarly that thirty-year period since *c* : 1865 : (earlier cold periods are hereby excluded) when the mean temperature was at its minimum. This map extends the information given in Fig. 1 and closely corresponds to Fig. 4.

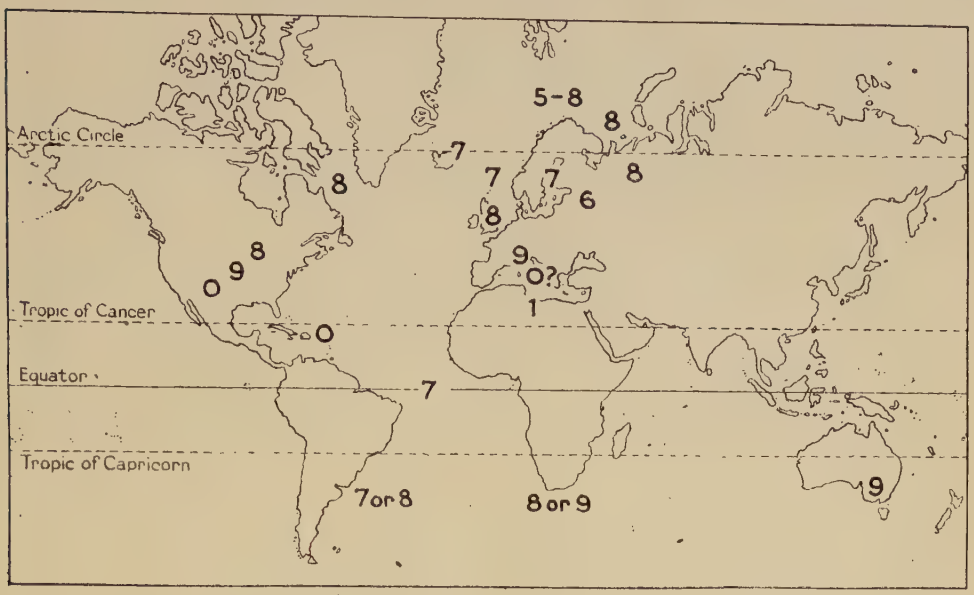

Figure 5. The last T-min time : that 30-year period (since 1851/80) in which mean temperature was the lowest.

Careful comparison of Figs. 1 and 2 shows that the T-min preceded the P-max by about ten years. Comparison of Figs. 4 and 5 shows that this may be true more generally.

(e) *The pattern of climatic fluctuation*

The southward progression of the features of the various trend-curves (the P-max and associated T-min and R-min) during the past century enables a " persistent anomaly pattern " of climatic fluctuation to be deduced.

Whilst the P-max lies to the north, there is a period of excessive E. or NE. winds *i.e.* a continental phase. After this comes the P-max or anticyclonic phase and, as the P-max passes to the south there is a W.-SW. or maritime phase.

The south-steering of the phases implies that mean pressure tends to fall for an excess of W. or SW. winds and to rise for an excess of E. or NE. winds. This is in marked contrast to ordinary synoptic experience (except *e.g.* in certain autumn situations in West Europe) but the rate of pressure change is extremely slow and the degree of this change is extremely small.

The wind-changes during the process explain why the turning points of the different meteorological elements do not synchronize. Thus the T-min should in West Europe tend to occur at the end of the NE.'ly phase just before the P-max. This can readily be seen to be true by comparing Figs. 1 and 2 or Figs. 4 and 5. The R-min should similarly occur at the end of the NE. phase at R-west sites such as West Scotland or Nantes. This explains why in Fig. 3 the rainfall curve for England seems to lag behind the curves for the other stations. Curves for R-east sites lag behind still more (*cf.* Fig. 6).

To complete the pattern, the wet periods at the beginning and end of this sequence have been labelled Frontal-A and Frontal-B. It can (Table II) be shown that in Britain (at least) these periods of lower pressure were associated with high rainfall and a marked temperature gradient from north to south. Beyond that the similarity cannot be pressed ; the Frontal-A period was predominantly NE.'ly and continental, the Frontal-B SW.'ly and maritime.

TABLE I. IDEALIZED STANDARD ANOMALY PATTERN FOR NW. EUROPE AS DEDUCED FROM THE SOUTH-STEERING PROCESS COMPARED WITH PERIODS ACTUALLY OBSERVED TO CORRESPOND

Stage	Pressure	Wind Excess	Weather	Temperature	Temperate Gradient N.–S.	South Scandinavia	Britain	North Italy	U.S.A.
						All dates are 30-year periods			
Frontal-A	Low	S. to SE.	Often wet	Warm	High	—	1875	1885	—
Continental	Rising	E. to NE.	Dry R (West)	Cold	—	1875	1885	1895	1905
P-max	High	N. to NW.	Dry	Cold	Low	1885	1895	1905	1915
Maritime	Falling	W. to SW.	Dry R (East)	Warm	—	1905	1905	1915	1925
Frontal-B	Low	S. to SE.	Often wet	Warm	High	1915	1915 & '25	1925	—

(g) *The pattern in the British Isles*

The five phases of Table I are admirably reflected in British climatic variations since 1860, as shown in Table II and even in Table III, where the decades are studied individually.

TABLE II. THE FIVE STAGES IN ENGLISH CLIMATE. 1861—1940 RELATIVE TO 1901/30 NORMALS

Stage	Period	Pressure	Pressure Gradient SSE.-NNW.	SW.-Wind Excess	RAINFALL England	RAINFALL "Area" Sites	RAINFALL R (East) Sites	Temperature England	Temperature Gradient England
Frontal A	1861–90	+ 3	— 8	— 4	— 2	— 3	+ 7	—20	+ 2
Continental	*c. 1885*	+ 9	—10	—10	— 3	— 4	+ 6	—21	— 4
P-max	*c. 1895*	+19	— 7	— 6	— 5	— 7	+ 1	—18	— 6
Maritime	*c. 1905*	+13	— 5	— 5	— 2	— 4	+ 1	— 5	— 2
Frontal-B	*c. 1915*	+ 0	+ 0	+ 0	+ 0	+ 0	+ 0	+ 0	+ 0
or	*c. 1925*				(+ 2)			+17	— 4

Pressure is in in. x 100. Mean of five " areas."
Pressure gradient (in. x 100). Thames Valley minus Scottish Lowlands.
SW. wind excess. Edinburgh and London (Brooks 1933). Per cent. See Brooks 1933 for units.
Rainfall percentage. England (1860-89 *et seq.*) according to Glasspoole 1933. See also Brooks 1949, p. 309.
,, ,, Area sites (Mean Greenwich and Oxford).
,, ,, R (East) sites (Mean Edinburgh and York).
Temperature. Mean Oxford, Greenwich, Lancashire, Durham, Edinburgh. °C x 10.
Temperature – Gradient Difference Oxford – Greenwich minus Edinburgh – Durham. °C x 10.

TABLE III. Decadal types in English climate relative to 1851/1900 normals

Decade	Type	Pressure	Pressure Gradient	SW. Wind Excess	Rainfall England	Temperature North England	Temperature Thames	Temperature Difference S—N.	Temperature Amplitude "England"
1851–60	Easterly	+ 7	— 10	(+ 1)	98	— 1	— 1	0	+ 2
61–70	South-west	— 3	+ **19**	+ **4**	96	+ 3	+ 4	+ 1	— **5**
71–80	Frontal	— 20	— *9*	— *3*	111	— 1	— 1	0	+ *3*
81–90	Anticyclonic	+ 4	— 2	— 2	102	— 4	— 5	— 1	— 3
91–00	Anticyclonic	+ 16	+ 1	— 2	97	+ 3	+ 3	0	+ *3*
1901–10	Anticyclonic	+ 6	+ 3	+ 7	97	+ 0	+ 1	+ 1	— 6
11–20	West	— 14	+ 3	+ 5	106	+ 4	+ 3	— 1	— **13**
21–30	Maritime	— 23	+ **14**	+ **12**	106	+ 5	+ 6	+ 1	— 9
31–40	South-east	(+)	—	—	102	+ 11	+ 9	— 2	+ 2
41–	Anticyclonic	+	—	—	*c.* 96	+			

Sources of data as in Table II, except for Temperature series. "*North England*" is mean of Edinburgh, Durham, Lancashire, °F x 10; "*Thames*" of Oxford and Greenwich °F x 10; "*Amplitude*" is summer minus winter mean of Lancashire and "Holland" (Labrijn) in °C x 10.

Bold Type = Maritime conditions. Italic Type = Continental conditions.

The wet Frontal-A period of the seventies is well known and was even remembered until quite recently in agricultural circles. This wetness had made its appearance during the sixties (Fig. 3) in West Scotland, and by the seventies, when England was so wet, North-West Britain was already becoming dry. Early Scottish information was not sufficiently abundant to be plotted on Dr. Glasspoole's (1933) maps but curves for various stations are given by Goldie and Carter (1939) who make a significant generalization, a rule understandable by applying the south-steering process to R (west) stations. They hint at the way in which new rainfall trends make their first appearance in North-West Scotland (*cf.* Fig. 3). They state "one gets the impression of a slight lag in the variations of the western as compared with the north-western . . . ." Similar curves for SW. Wales and London (Salter 1921, p. 219) show that if they had extended their studies south of the border they would have found this lag successively greater southwards and eastwards, as indeed it should be in accordance with any south-steering process. The transference of the wet (Frontal-A) belt from North Norway to Brittany (by c. 1890) is well-shown on Arctowski's map (1936, Fig. 13, p. 33).

The drop in temperature associated with the "easterly" type of the continental stage is well-marked in Iceland in the sixties, Scotland in the seventies (*cf.* Fig. 1) and England (Callendar 1938b, p. 654) in the eighties, and the T-min time is associated with some particularly cold spells in the period 1890-95. The change from wet to dry begins in 1879 in NW. Scotland (McClean 1925) and in the mid-eighties in most of the rest of Britain.

The P-max period is associated with consistently dry weather. In his study of wheat prices Lord Beveridge (1922) considered various West European rainfall series and noted the contrast between the irregularity of 1857-1882 and the constancy of 1885-1902. In England the wettest year of the 1890's had only 111 per cent rainfall but on the other hand even the driest year had 83 per cent, *i.e.* a difference of only 28 per cent between the wettest and driest year compared with 53 per cent difference in the preceding and 47 per cent difference in the following decade.

In West Scotland (Figs. 3 and 6) this dryness is greatest in the easterly eighties, but generally in England the nineties are the driest ; the period 1891/96 is remarkable for some very dry months. In Dorset the dry period (1887-1908, see Good 1942) does not begin until the dry period in North Scotland (1879-89/91) is nearly over. Places sheltered from the west (see Fig. 6) have an R-min about *c. 1904* and locally in East Lincolnshire and parts of Kent it is as late as about *c. 1914*.

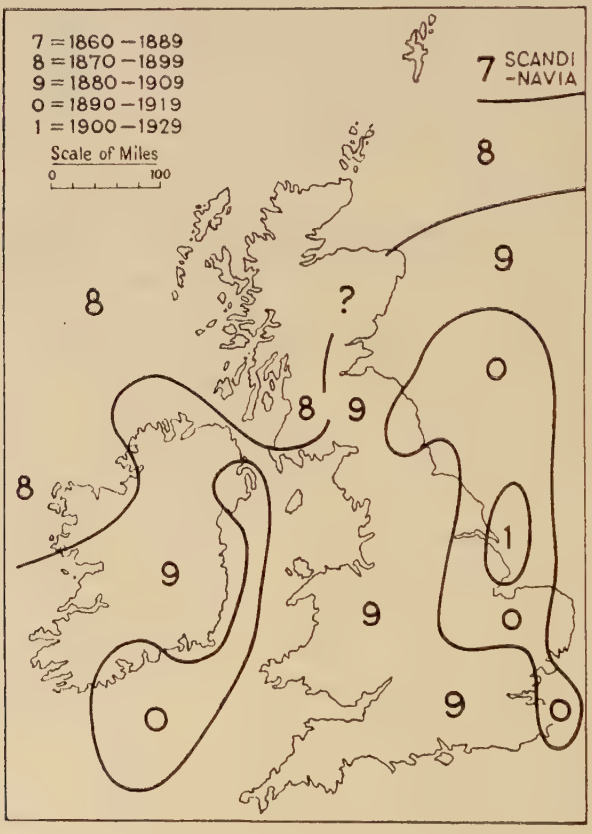

Figure 6. The R-min in Britain. (Based on Glasspoole's Rainfall Maps)

The next change soon showed itself in Scotland ; the wet period begins about 1890 in the NW. (McClean 1925) and before 1900 in the SW.; but it does not reach England until some years later. SW. winds become more frequent and the mean pressure begins to fall and the temperature to rise.

In the 1920's barometric pressure was very low in Scotland and the wetness of the Frontal B stage is reminiscent of the 1870's, and was partly responsible for another agricultural depression.

Ten-year means do not eliminate (*e.g.* 1850's, 60's, 1900's, 1910's) many " temporary " phases, and even analogies such as the above cannot be pressed. In accordance, however, with our dictum that rainfall trends make their first appearance in NW. Scotland, dry conditions which affected this area in the thirties have during this present decade affected much of England. There had moreover been some change towards continental type (see Fig. 7) in the thirties.

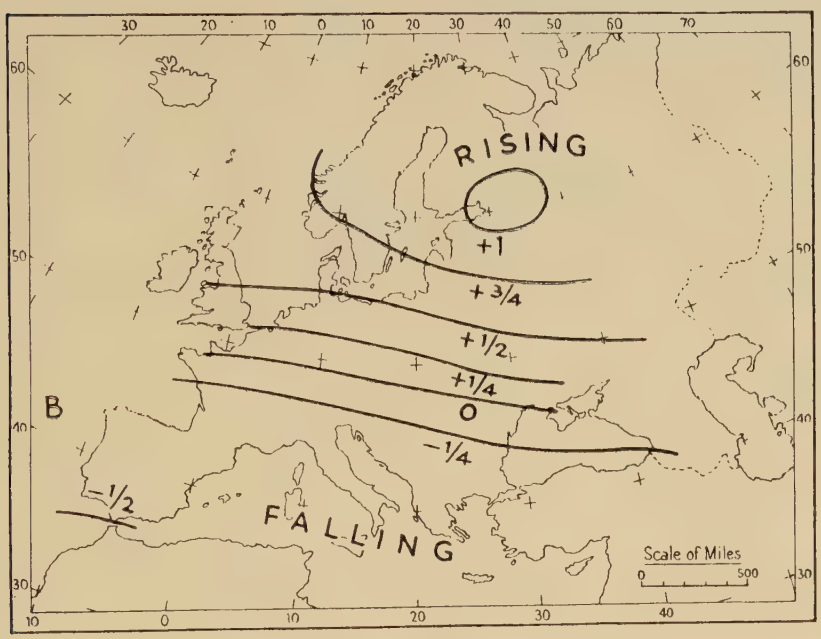

Figure 7. Isallobars : Pressure difference (mm) 1931/40 minus 1921/30 to illustrate the decrease in circulation.

Tables IV and V show, for comparison with Tables II and III, the pattern in other parts of Europe. Despite minor differences the main features of Table I are preserved and, in comparison with Britain, occur about a decade earlier in Scandinavia and a decade later in North Italy.

TABLE IV. THIRTY-YEAR MEANS IN SOUTH SCANDINAVIA (60°N.)

(Data from Hesselberg and Birkeland's papers)

Thirty Year Period	Type	Pressure Oslo Bergen mean mb x 10	Temperature Oslo Stockholm mean °C x 10	Rainfall (S. Norway) percentage
1841 – 1870 :		+ 6	— 1	—
c. 1865		+ 5	— 2	—
c. 1875	Cold phase	+ 5	— 5	— 8
c. 1885	P-max	+ 6	+ 1	— 7
c. 1895		+ 5	+ 5	— 7
c. 1905		+ 2	+ 9	— 3
c. 1915	P-min	— 1	+ 12	+ 0
c. 1925	Backing winds	+ 0	+*c.* 20	+ 1

TABLE V. DECADAL TYPES IN NORTH ITALY (45°N.)

(Data for the pressure and wind anomalies are based mainly on the Trieste, Venice, Vienna, Basle and Genoa pressure series)

	Temperature °C x 10				Pressure mm x 10 North Italy	Wind Anomaly	Decadal Type	Thirty-year Type		
	Rome	Trieste	Bucharest	Mean						
1851/60	— 3	?	+ 3	+ 0	— 5	E.				
61/70	+ 2	+ 2	+ 5	+ 3	+ 2	—	Dry, warm		(Warm)	
71/80	+ 1	— 2	+ 0	+ 0	— 2	SW.		SW. Maritime	(Warm)	*c. 1875*
81/90	— 1	— 3	— 7	— 4	+ 0	—		P-min Frontal-A	(Cold)	*c. 1885*
91/00	+ 2	+ 1	+ 0	+ 1	+ 2	NE.		NE. Continental	(Cold)	*c. 1895*
1901/10	— 1	— 1	+ 0	— 1	+ 0	NE.		P-max	(Warm)	*c. 1905*
11/20	+ 1	+ 0	+ 1	+ 1	+ 0	SW.			(Warm)	*c. 1915*
21/30	+ 6	+ 3	+ 4	+ 4	+ 0	SW.	Dry, warm	SW. Maritime	(Very warm)	*c. 1925*
31/40		+ 0			— 2	SE.				
	1851/1900 Normals				Estimated from Pressure Maps 1901/30 Normals					

Sources: Rome Knoch (1947) 15·3°
Trieste Polli (1942) 14·06°
Bucharest Knoch (1947) 10·6°

(h) *The pattern by decades in the U.S.A.*

A similar pattern of climatic fluctuation is applicable to the U.S.A., but, as reliable records seldom extend further back than 1885, in Table VI decadal rather than 30-year data are given. An easterly period can however be identified *c. 1905* and a westerly period *c. 1935*, with an intervening P-max about *c. 1915*. The pattern therefore occurs about 20 years later than in Britain. As the U.S.A. is approximately the latitude of the Azores this conforms to the general scheme of Fig. 4.

One important difference that should be noted is the relation between the rainfall and the pressure trends. Tannehill (1947) has shown that in the U.S.A. this depends on the *weakness* of the circulation ; in the terminology of this paper the U.S.A. (sheltered by the Rockies from the west) as a whole acts as an R-east site.

TABLE VI. Decadal patterns in the U.S.A. (relative to 1911/40 normals)

Decade	Pressure Mid-U.S.A.	Pressure Gradient South minus North	Rainfall All U.S.A.	Rainfall West Central	Temperature North Central	Temperature SE.	Thirty-year Type
1881-1890					—17	— 1	
1891-1900	— 2	+ 1 (W)	98	100	— 9	— 5	
1901- 10	+ 3	— 3 (E)	101	105	— 6	— 6	Easterly
11- 20	+ 3	— 7 (E)	102	103	— 9	— 5	P-max
21- 30	+ 2	+ 1 (W)	100	101	— 1	+ 2	
31- 40	— 4	+ 9 (W)	97	93	+ 9	+ 4	Westerly
41- 50							Frontal B (?)

Pressure and pressure gradient data from graphs given by Kincer (1940).

Rainfall data in percentages derived from data in Tannehill (1947, Tables II and IV, pp. 240 and 244).

Temperature data from *World Weather Records* kindly supplied by Callendar (°F x 10).

North Central = Marquette and Bismarck (corrected). Other stations show a similar tendency, provided " Bismarck " record published in *World Weather Records* was corrected for " city " influence at a rate of 2°F per century.

South-east = Nashville, Galveston and Key West.

In the 1930's there was an abnormal westerliness, associated with the Dust-bowl droughts and some record low levels of the Great Salt Lake (*cf.* R. L. Ives 1948).

An easterly excess had already commenced in North Canada by 1930 and spread to South Canada during the next decade. This is presumably associated with a frontal-B stage in the U.S.A. in the forties with a reversal of trends and prospects of higher rainfall in that country.

4. The oceanic basis of pressure anomalies

World charts of pressure anomalies for decades in terms of longer periods have all (*e.g.* Wagner 1929, p. 43 ; Scherhag 1931, Fig. 6, Table X ; Lysgaard 1949) shown a common feature, significant in any explanation of south-steering. *Pressure anomalies are greater over oceans than over continents.* Moreover, these larger anomalies lie west-east across the oceans. This suggests that the south-moving anomaly-patterns may be generated over the oceans. If this is true it follows as a corollary that the *excess* wind component in Western Europe should normally back rather than veer. The actual mean wind should veer slightly as a P-max approaches from the north, *i.e.* as the secular mean pressure rises. On the other hand, from *c. 1895* to *c. 1930* mean pressure was falling in North-West Europe and a backing of the prevailing wind should be expected.

5. The backing of the prevailing wind

A backing of the prevailing wind has already been noted in the Dutch wind records by van Veen (1940) and Labrijn (1945). It has been claimed that there has been a secular change of 20° since the eighteenth century and that (Braak 1942) the orientation of recently fallen trees is backed from those that fell long ago. However this may be, reliable evidence of wind and pressure changes does indicate a real change between 1871/1910 and 1911/40, *i.e.* the period required by our corollary. In the former period the sea-level pressure was higher at Valentia (SW. Ireland) than at Copenhagen ; in the later period the position has been reversed. In the Oslo wind records (Hesselberg–Birkeland 1943, Fig. 23, p. 34) the same increase of southerly component is found in all four seasons.

TABLE VII. The south-east component of prevailing winds and corresponding pressure changes 1901/30 normals

(Note : The early wind-data are in brackets because pressure maps do not confirm the strong NW. components indicated)

	Prevailing Wind SE. component			Pressure Gradient ENE. minus WSW. (Upsala + Copenhagen) minus (Edinburgh + Valentia) mb x 100
30-Year Period	Edinburgh and London	Amsterdam Utrecht De-Bilt	Oslo	
1841 – 1870 :	(— 11)	(— 20)		+ ?
c. 1865	(— 9)	(— 19)		+ ?
c. 1875	(— 12)	(— 9)		— ?
c. 1885	(— 11)	(— 10)	(— 14)	— 9
c. 1895	— 5	— 8	— 12	— 21
c. 1905	+ 3	— 10	— 22	— 23
c. 1915	+ 0	+ 0	+ 0	+ 0
c. 1925	+ ?	+ 0	(+ 14)	(— 7)
Source	Brooks 1933	Labrijn 1945 in ref. and ms. data	Hesselberg-Birkeland 1943	

6. South-steering in the separate seasons

South-steering appears to be most marked in the winter season but from Hesselberg and Birkeland's (1943, Fig. 4) charts it would appear to occur also in the other seasons. Moreover, the maxima and minima appear to occur earlier in winter and spring and later in summer (Table VIII) and autumn.

TABLE VIII. The P-max time in winter and autumn (*cf.* Hesselberg-Birkeland 1943, Fig. 4)

	P-max Winter	P-max Autumn
Iceland	1884	
Norway	1888/85	1885
Scotland	1888	1907
London	1894	1912

South-steering before 1860

Before 1860 pressure trends, except in the winter season, are smaller than the errors inherent in the data. However, in Table IX the dates of the winter maxima and minima are summarized from detailed charts and tables in the work of Hesselberg and Birkeland (1943). There is some indication that south-steering is the rule in temperate Europe. Table X shows a similar table for *annual* temperature, using thermometric series and, for the eighteenth century Arctic ice and ice-melting statistics.

TABLE IX. The thirty-year periods of maximum and minimum pressures since records began (winter season)

(Data based on tables in Hesselberg-Birkeland 1943)

	P-min <1840	P-max <1865	P-min 1841/90	P-max >1865	P-min >1895
Greenland	—	—	—	—	1917
Iceland	—	—	—	1884 (66?)	1916/17
North Norway	—	—	—	1885	1912/13
South Norway	—	1834	1845 or 60	1883	1912
Upsala	—	—	—	1883	1912
Edinburgh	1803	1834	1860	1888	1913
London	1805	1849 (85?)	1862/64	1894	1922 (11?)
Azores	—	—	1888	1917	—

TABLE X. The thirty-year periods of maximum and minimum temperatures since records began (year)

	T-max	T-min	T-max	T-min
	<1850	1780/1850	1801/1900	<1850
Iceland and North Scandinavia	⩽1770	1795	1855 ('35)	1885 ('75)
NW. Europe	1765	1805	1835	1895
N. Italy	1785	1845 ('25)	1865	1905

The tables appear to suggest that south-steering is usual in West Europe at least south of Iceland and Central Norway. There is some evidence to show that in the Arctic itself north-steering occurs and the northward movement of the winter P-min from Norway, *c. 1912* to Greenland *c. 1917* explains the sudden rise of temperature which did not reach Spitsbergen until the latter date (*cf.* Eriksson 1943).

A " pattern " of the Little Ice Age was recently set out in tabular form (Schove 1949, p. 176) for the region between 40° and 55°. Evidence does not yet permit one to determine whether the various phases occurred earlier *e.g.* in Belgium than in Italy.

7. Theory of south-steering

The various theories of climatic changes classified by Brooks (1949) provide no basis for *persistent* south-steering of anomaly patterns. The recent description (Willett 1949) of climatic variations in terms of expanding and contracting circumpolar vortices would lead one to expect occasional south-steering but also occasional north-steering. Is the process described in this paper an accidental phenomenon or does it represent a law of climatic variation ?

To clear the ground before giving a satisfactory answer to this question I can only appeal for further tables from the Pacific and the southern hemisphere corresponding to those given here.

An anomalous high frequency of SW. winds produces concurrently a positive anomaly of sea surface temperature in the regions over which the wind is blowing. Experience suggests that such anomalies are obliterated in a period of weeks, once the mechanism that produced them is removed.

If such anomalous SW. winds persisted over a decade it seems possible that the temperature below the surface would be raised and that the pressure of the subsequent decade might thereby be lowered. Conversely, an excess of NE. winds would produce cooling and a gradual rise of surface pressure. Some such mechanism would seem to account for the dynamics of the south-steering process.

In conclusion, I should like to thank many persons, especially those whose names are starred below, for statistics useful in testing the concepts of this paper.

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Troughs in the Upper Westerlies and cyclonic developments in the Nile Valley

By M. G. EL-FANDY

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SUMMARY

In the Middle East Area (M.E.) troughs in the upper westerlies are found, generally, at levels over 2 km above M.S.L. intruding into low latitudes as far south as the Northern Sudan (lat. 20° N.). These troughs usually travel eastwards, but tend to trail over the NW. of the Abyssinian Plateau. They also frequently remain stationary for about three days (on the average) over the SE. Mediterranean, owing to the effect of the plateau of Asia Minor.

At the southern limits of these troughs, centres of convergence are usually set up within the westerlies, which have thus extended (at upper levels) into low latitudes, between lat. 22° N. and lat. 15° N. For the purpose of studying them the stream-line map has been found the most satisfactory ; the usual pressure map is of little assistance.

As a rule a cyclone (say of type " A ") tends to form at a centre of convergence, and travels towards the NE., NNE., or even N.; the northward movement of the cyclones being due to the tendency for them to move towards the " centres " of the quasi-stationary troughs over the SE. Mediterranean. Cyclones may eventually appear on the surface synoptic charts as shallow areas of low pressure.

Another set (say of type " B ") of upper-air cyclones, which move south-westwards, tends to form farther south by the setting up of wave-like perturbations in the usual E. — NE. upper current of the atmosphere of the Central Sudan. These perturbations appear at the time of re-establishment of the E. — NE. current over the N. Sudan with the northward retreat of the westerlies, extend into low latitudes, and generally, when an upper-air cyclone of type " A " has reached the M.E., another cyclone of type " B " develops over the East-Central Sudan.

The analysis has some value in forecasting upper winds on the Cairo—Khartoum air-route and the local weather associated with these cyclones, and also in studying the general circulation in these latitudes, more especially the characteristic features of these cyclones.

1. General aspects of the problem and the technique

Analysis of the last war's weather maps of the M.E. (with an increased number of reporting centres) has shown that the so-called steady wind circulation of the M.E. and accompanying settled weather in summer (mainly June to August, Kendrew 1927), which are accepted in climatological books, are liable to be interrupted. Even in the upper air, pilots flying along the air-route Cairo-Khartoum report the occurrence of cyclones which are not directly traceable on the usual pressure maps, and mention these cyclones as causing drift and sometimes giving rise to conditions unfavourable to aircraft in flight. The conclusion has been reached that perturbations and cyclonic developments, sometimes quite marked, occur in the upper air and give rise to

(a) deviations from normal conditions in the windfield,

(b) cloud formation and

(c) the occurrence of " hot " spells over the Middle East and N. Sudan generally.

In autumn (mainly September-November) developments are mainly in the form of shallow lows which are frequently associated with thunderstorms (El-Fandy 1948). Ashbel (1938) discussing the cause of these thunderstorms, concludes that they are due to the influence of what he calls " barometric lows from the Red Sea," but he does not go beyond this conclusion.

The changes of surface pressure associated with such perturbations and developments are usually small (not exceeding 2-4 mb) and are often disregarded by forecasters. The usual pressure maps fail to show (or even to conform closely to) the windfield. For this reason stream-line analysis has been adopted by mapping the wind field itself at different levels and drawing the instantaneous stream-lines. Throughout the paper the 3-km level has been taken as a standard level, as, at 4 km or more, observations are frequently not available. The wind direction at each station is shown by a short arrow, the speed being denoted by barbs (1 barb = 10 km/hr).

Stream-lines are drawn to fit the wind arrows, but in areas for which observations are not available the form of stream-lines has been deduced from knowledge of the general circulation and the probable sequence of day-to-day changes. With experience it becomes possible to draw stream-lines so that their distances apart are inversely proportional to the wind speed.

In this way characteristic flow patterns, which are of value in forecasting weather in these regions (El-Fandy 1949) have been obtained. Some of the stream-lines end in areas which can be regarded as areas of convergence (Forsdyke 1949). The outstanding region is that from NNW. to West of Abyssinia. Numerous clear examples of convergence and subsequent developments within this region can be given.

2. Examples of convergence and subsequent developments

(a) *General*

Fig. 1 represents the sequence of changes which usually take place in the wind field at 3 km. It gives a series of stream-line charts from 12 to 16 October 1943. On the morning of the 12th a centre of convergence C_1 appears over Atbara at the SW. limit of a trough which has advanced to Northern Arabia. On the morning of the 13th, however, this centre of convergence is replaced by a cyclone which approaches the Central Red Sea during the afternoon of the 13th and northern Arabia on the afternoon of the 14th. A minor cyclone (resulting from a centre of convergence C_2 on the afternoon of the 13th) also advances towards the Northern Red Sea during the afternoon of the 14th.

The recession of these cyclones and the re-establishment of the usual E. — NE. current of the Northern Sudan are followed by the setting up of centres of convergence C_3 within the E. — NE. flow, and the consequent development of another set of cyclones travelling SW. Fig. 1, in fact, gives a general view of the state of affairs when troughs have trailed over the NW. of the Abyssinian Plateau.

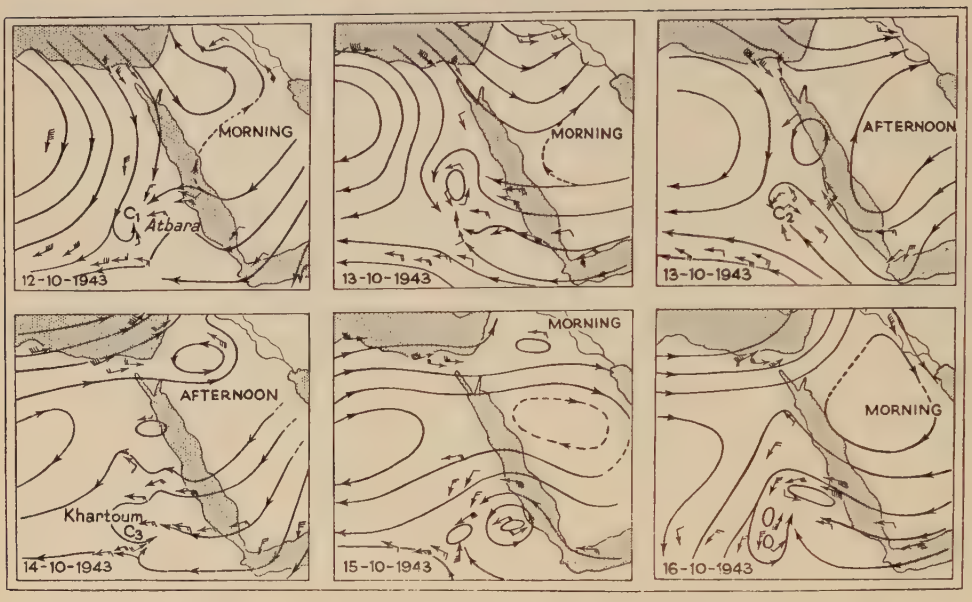

Figure 1. Stream-line charts, 12 to 16 October 1943

(b) *Quasi-stationary troughs*

In Fig. 2 another sequence of changes, from 26 to 30 October 1943, is given to show the development of a cyclone at the southern limits of a quasi-stationary

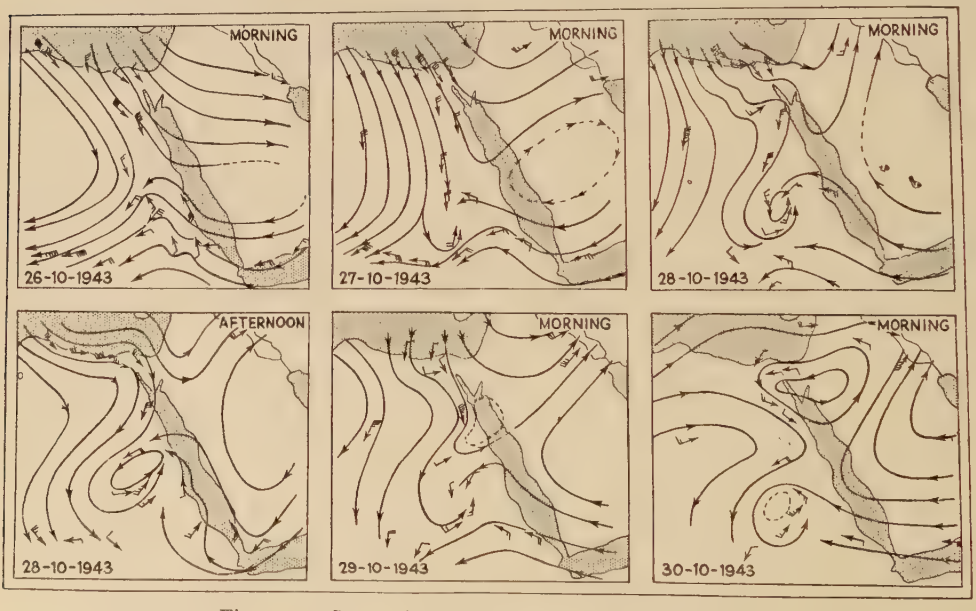

Figure 2. Stream-line charts, 26 to 30 October 1943

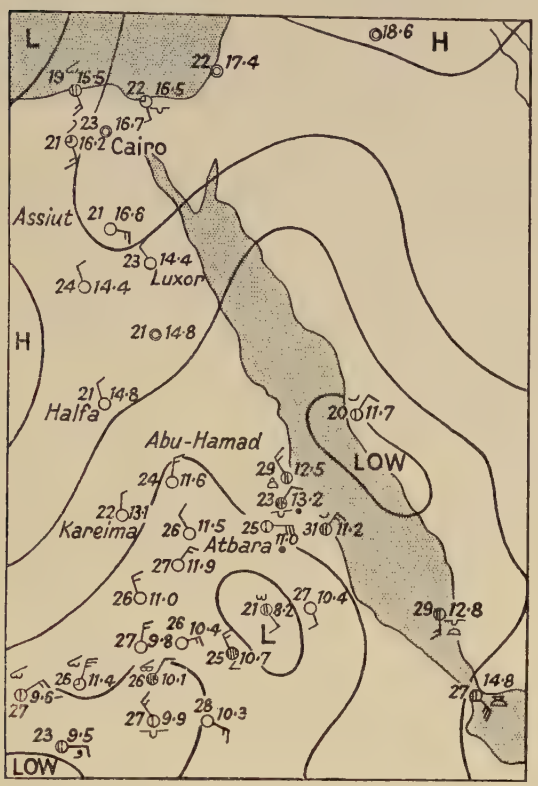

Figure 3. 0600 G.M.T. synoptic chart, 28 October 1943

trough and its subsequent displacement to the NNE. On the 28th the cyclone is seen approaching the Central Red Sea. It also appears clearly, in this case, on the 0600 G.M.T. synoptic chart of 28 October 1943, reproduced in Fig. 3. Notice the report of rain near the west coast of the Central Red Sea in Fig. 3.

On 30 October the same cyclone covers the M.E., resulting in an easterly flow over Egypt, notably near the coast. This cyclone, having collected water vapour from the SE. Mediterranean, gives instability showers near the west coast of Egypt. Under such conditions the synoptic situation is characterised by northward extensions of the low pressure system covering the Northern or Central Sudan. Forecasters can usually follow such extensions (or oscillations) and make use of them in forecasting warm spells or thunderstorms in the M.E. generally (El-Fandy 1948 and 1949).

(c) *Cyclones over Egypt*

In Fig. 4 is reproduced a typical example of a quasi-stationary trough over Egypt giving an active development which ultimately unites with the "centre" of the trough and is followed by the development of a cyclone travelling SW. over the central Sudan.

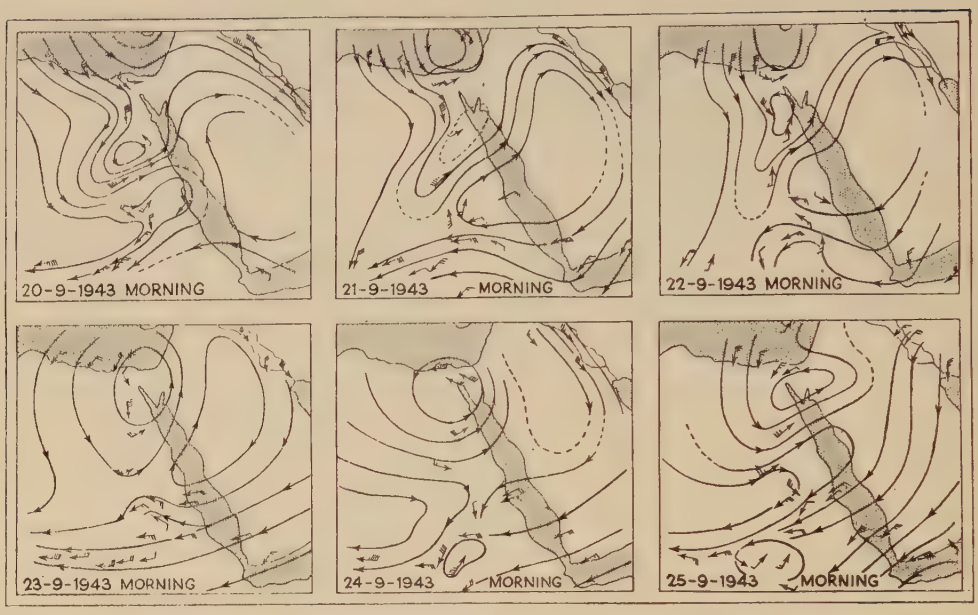

Figure 4. Stream-line charts, 20 to 25th September 1943.

Fig. 4 gives the stream-line charts from 20 to 25 September 1943. The 0600 G.M.T. synoptic chart of the 24th indicates the passage of a cyclone with about 2-mb fall of pressure within 24 hr over the area covered by the cyclone in the S. Sudan.

3. Upper winds on the Cairo—Khartoum air-route

Reports of such travelling cyclones in the upper air are of great value on the air-route Cairo—Khartoum, notably when the wind speed is great. An example is given by the cyclone of 16-17 August 1943. The pilot-balloon reports available from stations close to the area covered by this cyclone are given in Table I*. [Refer

TABLE I. Pilot-balloon observations, 16-17 August 1943.
(First three figures give direction in degrees east of north and last two figures give velocity in km/hr.

Date	Station	Height in kilometres above M.S.L.					
		0·6	1·0	1·5	2·0	3·0	4·0
16	Halfa ..	020 45	020 40	310 10	350 25	340 20	090 25
16	Abu-Hamad	050 10	060 10	040 20	050 35	070 45	160 25
16	Kareima ..	050 20	320 20	310 05	320 15	360 35	350 25
16	Atbara ..	320 20	300 20	300 20	290 30	240 40	— —
17	Cairo ..	320 10	020 25	010 35	020 30	060 30	— —
17	Assiut ..	360 20	350 35	340 40	320 40	320 45	— —
17	Luxor ..	350 30	340 45	330 40	300 40	200 25	250 60

* Another example of the marked deviations from average conditions in the wind field along this route occurred on 29 September 1943.

also to Fig. 3 in locating the positions of these reporting centres]. Notice that velocities of 40-60 km/hr prevail over Southern Egypt above 1 km on the 17th. On the same day much high and medium cloud is reported from stations in Southern Egypt. This is rather an abnormal meteorological feature for this area in summer. Barometers show local falls of pressure of about 2-4 mb in 24 hr.

4. Local weather associated with cyclones

Owing to the lack of sufficient water-vapour in the atmosphere of Egypt, Arabia and the northern Sudan, cyclones travelling north-eastwards generally show little or no activity beyond the formation of high and medium cloud ; but occasionally in the immediate vicinity of sources of water-vapour, such as the Red Sea or the SE. Mediterranean, they may give rise to thundery precipitation, notably in autumn (El-Fandy 1948).

In summer these cyclones, travelling NE., are usually associated with the spreading out of heat waves over the M.E. Over Egypt the heat waves may be shown by upper-air temperatures, say from near Cairo. Early morning upper-air temperatures then have values ranging from 28°C to 30°C at 300 to 1,000 m, with an almost dry-adiabatic lapse rate above to about 2,000 m. These temperatures are much higher than the normal for Cairo.

Cyclones moving SW. cannot be followed beyond the SW. Sudan, owing to lack of observations. However, it is suggested that the well known West African tornadoes may originate as cyclones of this type, intensified in their later stages by instability effects arising from the wide differences between the physical properties of the air masses which are drawn into their circulation from regions like the Sudan and the Gulf of Guinea, and which are brought into juxtaposition along the West African coast. This area, however, is a meeting place of air streams having the widely different characteristics necessary for the formation of active fronts (Forsdyke 1949).

5. Northward oscillations of the Sudan monsoon low

By the Sudan monsoon low is meant an oscillatory barometric minimum which in autumn is situated over the east-central Sudan (see Fig. 3). Northward oscillations of this low are generally due to the passage over the M.E. of troughs in the upper air, or developments of cyclones travelling north-eastwards (El-Fandy 1948).

Sometimes the oscillation is in the form of a northward extension (on synoptic charts) of the monsoon low. This is shown by 2-4 mb fall in pressure over Northern Sudan and Egypt (in particular over the northern Red Sea areas), and the ultimate inflow of a hot SE. current into the SE. Mediterranean. Rapid lifting of the SE. current by westerly air-currents from the Mediterranean gives rise to thunderstorms (*e.g.*, 23 October 1943).

6. Some characteristic features of cyclones "A"

The outstanding features of cyclones "A" are:

(1) When a cyclone has extended to the surface its axis is inclined upwards towards the NE.

(2) Convergence of winds is the cause of these developments.

(3) They occur in air-streams in which the velocity does not necessarily exceed 30-60 km/hr.

(4) The average period between two successive developments can be taken as six days. Table II gives a series of dates of developments of types "A" and "B" in four successive months. These dates are, in fact, the days on which cyclones appear on the stream-line charts. Dates between two brackets refer to developments of type "B." Notice the striking occurrence of one set after the other.

(5) The relationship of areas of convergence (or areas of cyclonic development) to areas of monsoon rain in the Northern and Central Sudan is slight. Even areas of large convergence in the N. Sudan show little rain.

TABLE II. Dates of cyclones in the upper air within the period July—October 1943

(Dates in parentheses refer to cyclones moving SW.)

July	August	September	October
6	3	(1)	7
—	9	9	13
15	(13)	(16)	(15)
(19)	16	20	19
21	(19)	(24)	24
(26)	22	27	28
29	(25)	(30)	31

Acknowledgments

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551.525.2

A note on nocturnal cooling

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SUMMARY

The published methods of calculating the minimum ground temperature after a clear night accompanied by radiational cooling are examined and a more comprehensive calculation is given which takes into account the physical properties both of the air and of the underlying surface. Some recent experimental data are adduced to support the contention that both the ground and the air supply the heat lost by radiation.

1. List of symbols

The symbolism is that used by Brunt (1939) and Frost (1948) and the numerical values used by these authors are given in brackets, all measurements being in cgs units.

z, t	vertical and time co-ordinates.
K_1	specific conductivity of heat in the earth's surface layers ($4{\cdot}7 \times 10^{-3}$).
ρ_1	density of the earth's surface layers (2·5).
c_1	specific heat in the earth's surface layers (0·2).
ρ	density of the air ($1{\cdot}28 \times 10^{-3}$).
c_p	specific heat of the air at constant pressure (0·24).
a, m	turbulence parameters as defined in Frost's paper (respectively 40 and 1/3).
R_N	loss of heat by nocturnal radiation, assumed constant ($2{\cdot}1 \times 10^{-3}$).
θ_0	potential temperature of the air at time $t = 0$.
θ	difference in the potential temperature of the air from its value θ_0 at time $t = 0$.
θ_g	value of θ at $z = 0$.
T_0, T, T_g	defined as θ_0, θ, θ_g referring to the surface layers of the earth.

2. Introduction

Brunt gives the formula

$$T_g = -\frac{2\,R_N\,t^{1/2}}{\pi^{1/2}\,\rho_1\,c_1\,K_1^{1/2}} \qquad . \quad . \quad . \quad . \quad . \quad (1)$$

for the fall in temperature at the earth's surface after a time t. Essentially he assumes that all the radiated heat is supplied by the earth's surface layers ; by

inserting the values of the parameters, suitable for a summer night, and taking t as 7×3600 sec, Brunt finds a value of T_g of —11°C.

Frost gives the formula

$$T_g = -\frac{R_N \left[(m+1)^2 \, at\right]^{m/(m+1)}}{a \, m \, \rho \, c_p \, \Gamma\left(1/(m+1)\right)} \quad . \quad . \quad . \quad (2)$$

The essential assumption made is that all the radiated heat is supplied by the air above the earth's surface ; by inserting the values of the parameters given above, and taking t as 7×3600 sec, Frost obtains a value of T_g of —15·6°C.

Both authors quote the mean fall at screen level for clear nights in June, given as 9°C by Johnson (1929), in support of their hypothesis. It is well known that the temperature fall at the ground may be considerably greater than that at screen level and Johnson's result represents a lower limit to the value of the temperature fall at the ground. Frost calculates the temperature fall at the screen level as 13°C which is rather high. In Brunt's calculation it is difficult to see how Johnson's figures, referring to screen level, can be used to compare theory and experiment, for the screen level is entirely outside the physical system envisaged, in which heat is lost by the earth alone ; a fall in screen temperature is indicative of heat lost by the air. Brunt's calculation would not indicate any fall in screen temperature ; in practice he has accepted the experimental fact that there is a fall in screen temperature which is less than that at the surface by a few degrees centigrade. Both the calculated results are of the right order yet it is difficult to believe that the physical processes, which are envisaged as separate by the authors, do not act in conjunction with one another. In this case the calculated minimum cannot be much more than half that calculated by either author, since the presence of an extra heat source inhibits the temperature fall and both the results are of the same order.

3. Experimental results

Experimental observations have been made recently in Texas (1949) of the temperatures at certain heights above the ground and, at the same times, of ground temperatures to a depth of twenty inches. Some of these observations were made during periods of nocturnal radiation. The results show clearly that heat is lost both from the ground and from the air. Fig. 1 shows a typical case of the temperature profiles both in the air and in the ground between 1830h and 0530h in September with a clear sky and uninhibited radiation. Using approximate values for the density and specific heat of both the air and the ground the amount of heat lost by the ground in a column of 1cm² cross-section is about 40 calories while that lost by a similar column of air extending upwards to 300 feet is about 20 calories. The observations do not extend above 300 feet so that R_N cannot be calculated ; its minimum value, assuming no heat is lost above 300 feet, is about $1{\cdot}5 \times 10^{-8}$ cal cm^{-2} sec^{-1} .

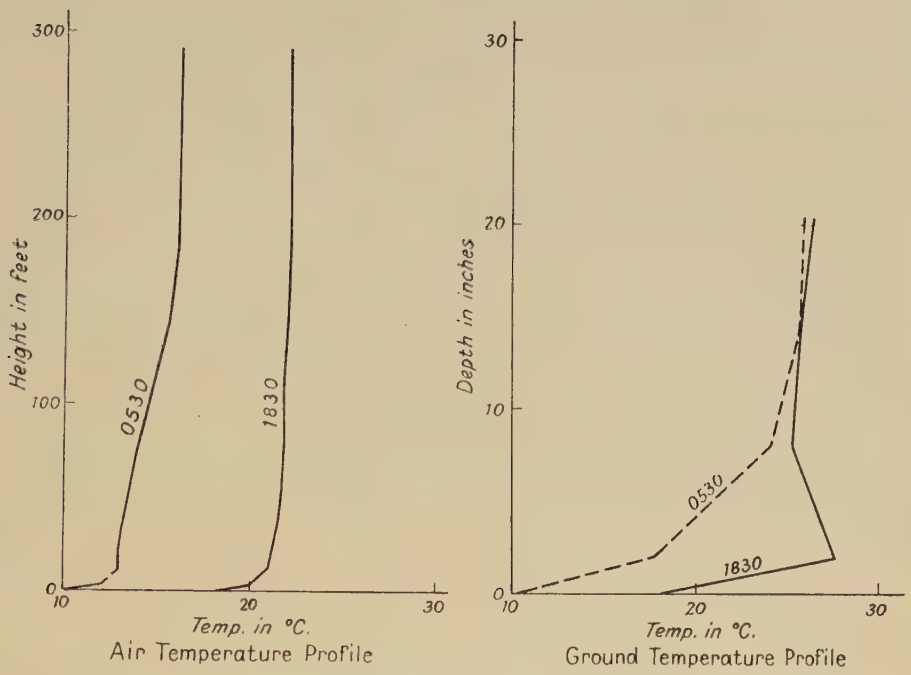

Figure 1. Temperature profiles in the air and in the ground at the beginning and end of a clear night.

4. The mathematical equations

With the notation as in paragraph 1 the equations are (Jaeger 1945)

$$\frac{\partial}{\partial z}\left(z^{1-m}\frac{\partial \theta}{\partial z}\right) = \frac{1}{a}\frac{\partial \theta}{\partial t} \qquad z \geqslant 0 \quad t > 0 \qquad . \quad . \quad . \quad (3)$$

$$\frac{\partial^2 T}{\partial z^2} = \frac{1}{K_1}\frac{\partial T}{\partial t} \qquad z \leqslant 0 \quad t > 0 \qquad . \quad . \quad . \quad (4)$$

where the axes are measured from the earth's surface, so that $z > 0$ is in the atmosphere and $z < 0$ in the earth. These equations define the modification of θ and T under the assumed diffusion laws. In the earth the diffusion is ordinary conduction of heat ; in the air the diffusion law follows the conjugate power law of Sutton (1947).

In addition the assumed boundary conditions are

(1) The temperature is continuous across the boundary.

(2) The total loss of heat is equal to the heat radiated at the boundary.

Expressed mathematically these boundary conditions are

$$\theta = T \text{ at } z = 0, \; t > 0 \qquad . \quad . \quad . \quad . \quad . \quad (5)$$

$$-K_1 \rho_1 \partial \Gamma/\partial z = -a \rho c_p z^{1-m} \partial\theta/\partial z + R_N \qquad \text{at } z = 0, \; t > 0 \quad . \quad (6)$$

Jaeger has solved these equations giving a series solution in terms of t.

It is shown in the appendix that the temperature fall at the surface, when both the air and the earth are considered as supplying heat, is given by

$$T_g = \frac{-R_N}{\lambda \rho_1 c_1 K_1^{1/2}} \left(\frac{t^{1/4}}{\Gamma(5/4)} - \frac{1}{\lambda} + \frac{2\sqrt{2}}{\pi} \int_0^\infty \frac{\exp(-u^4 t)\, du}{u^2 + \sqrt{2}u\lambda + \lambda^2} \right) \quad . \quad (7)$$

where

$$\lambda = \frac{a \rho c_p (4/3)^{1/2} \Gamma(3/4)}{a^{1/4} \Gamma(1/4) \rho_1 c_1 K_1^{1/2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

and m has been taken as 1/3, following Frost. For the values of the parameters adopted by Brunt and Frost, $\lambda \simeq 1/18$ and

$$T_g = -6{\cdot}3°\text{C}.$$

This value of T_g, which is about what might be expected taking into account both sources of heat, is too small. The values of the parameters used by the authors are therefore examined.

5. The values of the parameters

(*a*) In *The Physical Properties of the Soil* (Keen 1931) the author makes it clear (p. 309) that the density, ρ_1, which Brunt uses, is the apparent density*. The diagram (p. 319) of Patten's results over a dry fine sandy loam shows that the apparent density is 1·6. Most of the heat lost by the earth is drawn from the first few inches of the soil and it seems that a more appropriate value of ρ_1 is 1·6 and not 2·5. This increases the value of T_g as determined by Brunt by a factor of 25/16.

(*b*) Frost obtains his values of a and m from a series of values, given in a paper by Cowling and White (1941), of the diffusivity at the levels 1·2, 12·4, 30·5, 57·4 and 87·7m ; in essence he fits a power law az^{1-m} to the values given, so determining a and m. The values given by Cowling and White and used by Frost refer to the end of the night ; they are respectively 1,000, 4,500, 8,500, 12,000 and 20,000. Through the night, however, the values are smaller. It will be noted that the values given above at the end of the night are also the *upper* limits of the values at 2400h, *i.e.*, near the beginning of the night ; also at 0400h, Cowling and White give the values 785, 4,950, 6,500, 9,100 and 17,500 while at 0530h the values are (assuming that at 1·2m to be 1,000) 1,000, 3,200, 5,500, 7,700 and 9,350. All these values are, of course, only approximate from the very nature of the method of calculation; nevertheless it seems that Frost's value of a is too large, assuming that $m = 1/3$ is a fair approximation. Reducing the value of a

* The apparent density is the density as measured in a straightforward manner by weighing a sample of known volume. There is also a dry density which is obtained by finding the weight after baking in an oven at over 100°C (' dry ' soil taken from the earth always contains some water) and so finding the weight of water. From these determinations the weight and volume occupied by the soil are obtained and the dry or true density.

to about 70 per cent of that given by Frost (which preserves the value of λ), then

$$T_g \simeq -6{\cdot}3 \times 25/16 \simeq -10°\text{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

when both the earth and ground are considered as heat sources.

6. Usefulness of the methods

The utility of any of the above methods of estimating the fall of temperature at the ground is called into question. The wide variation of the parameters from place to place and time to time, and the difficulty of estimating some of these parameters, make the methods extremely difficult to apply in order to calculate the temperature fall. In fact the experiment might well be reversed and the measured temperature fall used to determine some of the parameters! The claim that the method of calculation does make is that the main physical features have been taken into account, although some recent work by Dr. G. D. Robinson (as yet unpublished) may indicate that radiative cooling direct from the air near the surface is also of importance.

Appendix

1. The solution of the differential equations leading to the formula (4) is given here. The convenient mathematical tool for solving the equations is the operational calculus. The mathematical formulae used are

$$z^n K_n(z) = 2^{n-1} \int_0^\infty \exp(-u - z^2/4u)\, u^{n-1}\, du \quad . \quad . \quad (1)$$

$$K_n(z) = K_{-n}(z) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$\frac{d}{dz}\left(z^n K_n(z)\right) = -z^n K_{n-1}(z) \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where $K_n(z)$ is the modified Bessel function of the second kind.

$f(t) \Longrightarrow \bar{f}(p)$ or $f \Longrightarrow \bar{f}$ implies that

$$\bar{f}(p) = p \int_0^\infty e^{-pt} f(t)\, dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and

$$f(t) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} e^{pt} \bar{f}(p)\, p^{-1}\, dp \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$a^{-n} 2^{n-1} \int_{a^2/4t}^\infty e^{-u} u^{n-1}\, du \Longrightarrow p^{\frac{1}{2}n} K_n(a\, p^{1/2}) \quad . \quad . \quad . \quad (6)$$

Of these the first three are to be found in text books dealing with Bessel Functions, (4) and (5) are a statement of the Fourier-Mellin Inversion Theorem to be found in

any textbook on the operational calculus and (6) is a particular result, to be found in the tables of transforms.

2. The operational form of the equations of paragraph (4) is

$$\frac{\partial}{\partial z}\left(z^{1-m}\,\partial\bar{\theta}/\partial z\right) = \frac{p\bar{\theta}}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$\frac{\partial^2\bar{T}}{\partial z^2} = \frac{p\bar{T}}{K_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

$$\bar{\theta} = \bar{T} \quad at\ z = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$-K_1\,\rho_1\,c_1\,\partial\bar{T}/\partial z = -a\,\rho\,c_p\,z^{1-m}\,\partial\bar{\theta}/\partial z + R_N \quad \text{at } z = 0 \quad . \quad (10)$$

3. Brunt's solution

Brunt reverses the sign of z in treating the earth and solves

$$\frac{\partial^2 T}{\partial z^2} = \frac{p\bar{T}}{K_1} \quad , \ z \geqslant 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

$$K_1\,\rho_1\,c_1\,\partial\bar{T}/\partial z = R_N \quad at\ z = 0 \quad . \quad . \quad . \quad . \quad . \quad (12)$$

The operational calculus readily gives the solution

$$\frac{\partial T}{\partial z} = \frac{2R_N}{\sqrt{\pi}\,\rho_1\,c_1\,K_1}\int_{z/2\sqrt{K_1 t}}^{\infty} e^{-u^2}\,du \quad . \quad . \quad . \quad . \quad . \quad (13)$$

which is the solution given by Brunt.

4. Frost's solution

Frost treats only the air and so solves

$$\frac{\partial}{\partial z}\left(z^{1-m}\,\partial\bar{\theta}/\partial z\right) = \frac{p\bar{\theta}}{a} \qquad z \geqslant 0 \quad . \quad . \quad . \quad (14)$$

$$-a\,\rho\,c_p\,z^{1-m}\,\partial\bar{\theta}/\partial z + R_N = 0 \quad at\ z = 0 \quad . \quad . \quad . \quad (15)$$

The appropriate solution of (14) is

$$\bar{\theta} = A\,\xi^{m/(m+1)}\,K_{m/(m+1)}(\xi) \quad \text{where } \xi = \frac{2z^{(1+m)/2}}{1+m}\sqrt{\frac{p}{a}} \quad . \quad . \quad (16)$$

Using (2) and (3)

$$z^{1-m}\,\partial\bar{\theta}/\partial z = z^{1-m}\,\frac{\partial\bar{\theta}}{\partial\xi}\cdot\frac{\partial\xi}{\partial z}$$

$$= -A\,\xi^{1/(m+1)}\,K_{1/(m+1)}(\xi)\left(\frac{1+m}{2}\right)^{\frac{1-m}{1+m}}\left(\frac{p}{a}\right)^{\frac{m}{1+m}} \quad . \quad . \quad (17)$$

Inserting the boundary condition (15) and using (1) with $z = 0$, after a little algebra

$$a\ \rho\ c_p\ z^{1-m}\ \partial\bar{\theta}/\partial z = \frac{R_N\ \xi^{1/(m+1)}\ K_{1/(m+1)}\ (\xi)}{2^{-m/(m+1)}\ \Gamma\left(1/(m+1)\right)} \quad . \quad . \quad . \quad (18)$$

and using (6)

$$\frac{\partial\theta}{\partial z} = \frac{R_N\ z^{m-1}}{a\ \rho\ c_p\ \Gamma\left(1/(m+1)\right)} \int_l^\infty e^{-u}\ u^{-m/(m+1)}\ du \quad . \quad . \quad (19)$$

where

$$l = \frac{z^{1+m}}{(1+m)^2\ at}$$

which is Frost's solution. It should be noted that Frost's direct solution of (14) and (15) is simpler, due to the simple boundary condition (15), but it does not lend itself to the more complicated equations of paragraph 2.

5. The solution of the equations

The appropriate solutions of (7) and (8) are

$$\bar{\theta} = A\ \xi^{m/(m+1)}\ K_{m/(m+1)}\ (\xi), \qquad \xi = \frac{2\ z^{(1+m)/2}}{1+m}\sqrt{\frac{p}{a}}$$

$$\bar{T} = B\ \exp\left(z\sqrt{(p/K_1)}\right)$$

where A and B are to be determined from the boundary conditions. The boundary condition (9) gives simply

$$B = A\ 2^{-1/(m+1)}\ \Gamma\left(m/(m+1)\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

and using (17) the second boundary condition gives

$$-K_1\rho_1 c_1\sqrt{\frac{p}{K_1}}\cdot B = A\,a\,\rho\,c_p\left(\frac{1+m}{2}\right)^{\frac{1-m}{1+m}}\left(\frac{p}{a}\right)^{\frac{m}{1+m}} 2^{\frac{-m}{1+m}}\,\Gamma\left(\frac{1}{m+1}\right) + R_N \quad . \quad (21)$$

Using (20)

$$A = \frac{-R_N\ 2^{1/(1+m)}}{\Gamma\left(m/(1+m)\right)\rho_1\ c_1\ K_1^{\frac{1}{2}}\ p^{\frac{1}{2}} + a\ \rho\ c_p\ (1+m)^{\frac{1-m}{1+m}}\ (p/a)^{\frac{m}{1+m}}\ \Gamma\left(1/(1+m)\right)}$$

while

$$\bar{\theta} = A\ \xi^{m/(1+m)}\ K_{m/(1+m)}\ (\xi)$$

Hence

$$\theta = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} A\ \xi^{m/(m+1)}\ K_{m/(m+1)}\ (\xi)\ e^{pt}\ p^{-1}dp \quad . \quad . \quad (22)$$

Eq. (22) gives the temperature profile in the air. At the level $z = 0$ using (1)

$$\theta_g = T_g = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} A\ 2^{-1/(m+1)}\ \Gamma\left(m/(m+1)\right) e^{pt}\ p^{-1}dp \quad . \quad . \quad . \quad (23)$$

The integrand in brackets in (23) reduces with $m = 1/3$ to

$$\frac{-R_N}{\rho_1 c_1 K_1^{\frac{1}{2}} p^{\frac{1}{2}} + a \rho c_p \left(\frac{4}{3}\right)^{\frac{1}{2}} \frac{p^{1/4}}{a^{1/4}} \frac{\Gamma(3/4)}{\Gamma(1/4)}} = \frac{-R_N}{\rho_1 c_1 K_1^{\frac{1}{2}} (p^{\frac{1}{2}} + \lambda p^{\frac{1}{4}})} \quad . \quad . \quad (24)$$

where

$$\lambda = \frac{a \rho c_p (4/3)^{\frac{1}{2}} \Gamma(3/4)}{\rho_1 c_1 K_1^{\frac{1}{2}} a^{\frac{1}{4}} \Gamma(1/4)} \quad . \quad . \quad . \quad . \quad . \quad (25)$$

Splitting (24) into partial fractions, from (23)

$$T_g = -\frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \frac{R_N}{\lambda \rho_1 c_1 K_1^{\frac{1}{2}}} \left(\frac{1}{p^{\frac{1}{4}}} - \frac{1}{p^{\frac{1}{4}} + \lambda}\right) e^{pt} p^{-1} dp \quad . \quad . \quad . \quad (26)$$

The first term in (26) simply gives rise to a term in T_g of

$$\frac{-R_N t^{\frac{1}{4}}}{\lambda \rho_1 c_1 K_1^{\frac{1}{2}} \Gamma(5/4)}$$

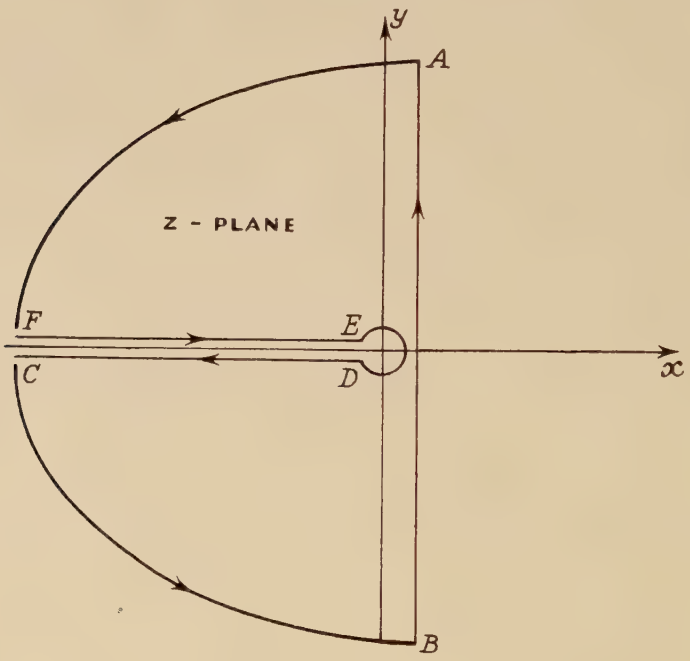

Figure 2.

To evaluate the second term the contour integral is taken round the path shown in Fig. 2 and the contribution from this term is found to be

$$\frac{R_N}{\lambda \rho_1 c_1 K_1^{\frac{1}{2}}} \left(\frac{1}{\lambda} - \frac{2\sqrt{2}}{\pi} \int_0^{\infty} \frac{\exp(-u^4 t)\, du}{u^2 + \sqrt{2}\, u\lambda + \lambda^2}\right)$$

Hence

$$T_g = -\frac{R_N}{\lambda\,\rho_1\,c_1\,K_1^{1/2}}\left(\frac{t^{1/4}}{\Gamma(5/4)} - \frac{1}{\lambda} + \frac{2\sqrt{2}}{\pi}\int_0^\infty \frac{\exp(-u^4 t)\,du}{u^2 + \sqrt{2}\,u\lambda + \lambda^2}\right) . \quad (27)$$

which is the formula given in the text (para. 4, Eq. (3)).

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The intensity of the net meridional circulation

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1. Introduction

Qualitative descriptions of the general circulation point out that there are three meridional circulation cells in each hemisphere. According to these descriptions, the boundary between the trades and middle-latitude westerlies lies roughly near 30° where surface pressure is high. Frictional outflow northward and southward is said to take place from the subtropical ridge, coupled with descent. Farther poleward, the average latitude of the polar front serves as the dividing mark between polar and middle-latitude cells. Here, air currents converge from both north and south and ascend.

It is the object of this paper to determine the intensity of circulation of these meridional cells and to estimate how effective they are in maintaining the heat and angular momentum balance of the atmosphere. This cannot be done with computations based on the pressure distribution (geostrophic wind) but only with use of resultant wind vectors. Riehl (1950) previously calculated the net meridional flow component at the surface between latitudes 25° N. and S. This note covers the area from 45° N. to 45° S.

2. Meridional wind profiles

The data for the computation of the meridional wind profiles (Fig. 1) were obtained from the *Atlas of Climatic Charts of the Oceans* (1938) which contains resultant wind vectors for 5°-squares based on observations dating back to sailing ship days. The net wind shown in Fig. 1 is based on data covering 80 per cent or more of the circumference of the globe south of latitude 25° N. The bulk of the continents of Asia and North America lies farther north, and over these continents wind vectors comparable to those over the oceans are not available. A glance at the streamline charts published by Brunt (1939), however, shows that in January the meridional wind direction over continents and oceans is alike (monsoonal outflow from continents). Indeed, there are only two small continental areas where the resultant wind is from the south at 40° N. During July, agreement is much poorer so that the northernmost part of the July profile of Fig. 1 is less representative.

In the other latitude bands, the meridional flow direction over continents and oceans also is largely parallel, and supports the profiles. At and south of latitude 40° S. observations are so sparse that different climatological atlases carry different resultant winds. Here, the exactness of Fig. 1 is again in doubt.

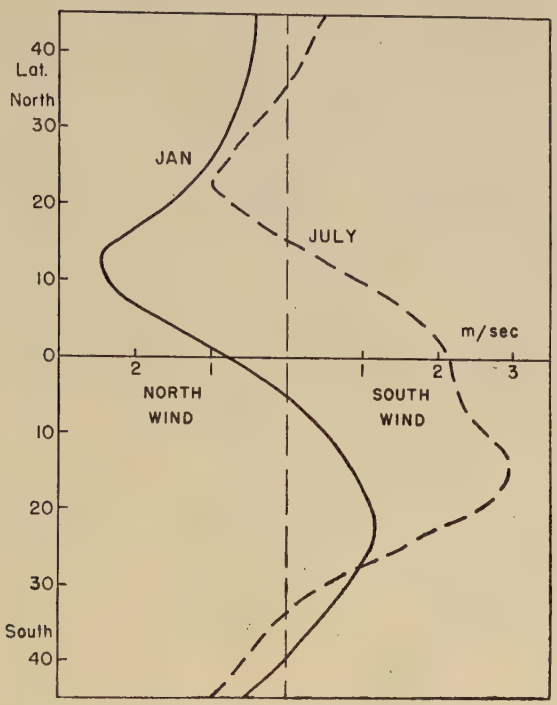

Figure 1. Net meridional wind profiles in January and July (m/sec).

Fig. 2 reproduces the mean sea-level pressure distribution as determined from Willett's *Descriptive Meteorology* (1944). These pressure profiles agree well with those given by Scherhag (1948). Fig. 3 shows the latitudinal profiles of velocity divergence, computed from Fig. 1 with the formula

$$\mathrm{div}_2\, V \equiv \mathrm{div}\, \bar{v} = \frac{\partial \bar{v}}{r\, \partial \phi} - \frac{\bar{v}}{r} \tan \phi \,. \qquad (1)$$

where $\mathrm{div}_2\, V$ is the horizontal velocity divergence, $\bar{v}$ the net meridional wind component, ϕ the latitude and r the radius of the earth.

Apart from the discussion given by Riehl (1950) on the latitude belt 25° N.-S., comparison of Figs. 1-3 brings out several points of interest. If we omit July in the northern hemisphere, we find that the latitude of the subtropical ridge line does not coincide with the latitude separating north and south components but lies 5° or more equatorward. Thus, a net transport of polar air takes place toward low latitudes across the high pressure belt. General circulation models do not show this. Transport must be even stronger a short distance above the surface at the poleward rim of the subtropical ridge, where friction acts to accelerate air toward the poles at the surface itself. Synoptically, we can picture that the equatorward transport of mass at the eastern ends of the subtropical cells exceeds the return flow at the western margins.

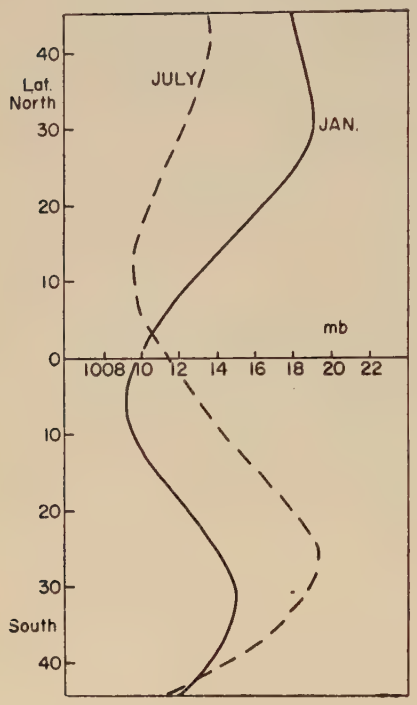

Figure 2. Mean latitudinal sea-level pressure (mb) profiles in January and July.

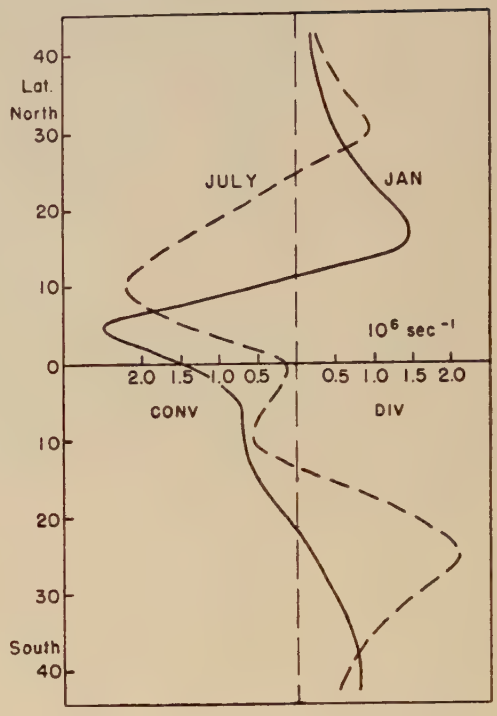

Figure 3. Net latitudinal divergence (10^6 sec^{-1}) in January and July.

Another discrepancy between Figs. 1-3 and previous models lies in the fact that the zone of maximum divergence does not coincide with the subtropical high-pressure centre in the northern hemisphere but lies well on its equatorward side. This feature is especially striking in January when the latitudinal difference is 10-15°. The principal descending motion occurs at latitudes well removed from the sub-tropical high. Thus the computations indicate a need for revision of textbook models of the meridional circulation. They show that the role of the subtropical highs must differ from that previously described.

3. Mass divergence

In the following we shall have to assume that the profiles of velocity divergence also represent those of mass divergence. It is well to point out that this will hold strictly only in the trade wind belt where wind steadiness is very high and density variations minute. Poleward from the trades the net meridional wind is the resultant of alternating north and south winds where the equatorward flow is correlated with higher density. If this factor is taken into account, the net mass transfer through the sub-tropical ridge becomes even larger. It would be a lengthy and perhaps impossible task, however, to calculate the actual flow of mass at the surface outside the trade wind belt. We shall assume that Fig. 3 represents mass divergence and we shall therefore arrive at an underestimate of the mean meridional circulation.

4. Vertical motion and strength of upper return flow

Upper air observations are too scare to permit determination of the meridional flow at upper levels as at the surface. Since we wish to obtain an estimate of the strength of the return circulation, we must make a suitable assumption about the depth of the layer for which the wind and divergence distribution as computed at the surface will hold. For reasons to appear shortly, we are interested in finding out the smallest possible intensity of the upper return circulation. Everyone should be agreed that we shall get minimum values if we assume that the surface circulation decreases linearly to the top of the friction layer (1 km) and that it reverses at that level. Under these circumstances, the vertical motion attains its largest values at the 1 km level, given by the relation

$$w_{\max} = -\frac{1}{\rho_{(1\text{km})}} \int_0^{1\text{km}} \text{div}\ (\rho v)\ dz \qquad . \quad . \quad . \qquad (2)$$

Fig. 4 shows the latitudinal distribution of $w_{\max}$. Because of the assumptions made, the shape of the curves in Figs. 3 and 4 must be identical. As expected, the magnitude of the vertical displacements is small. It attains 100 m day^{-1} in only a few places. In Figs. 1-3, the asymmetry between the hemispheres is striking. It is generally agreed that such asymmetries must find their explanation in the unequal amount and location of land masses in the two hemispheres.

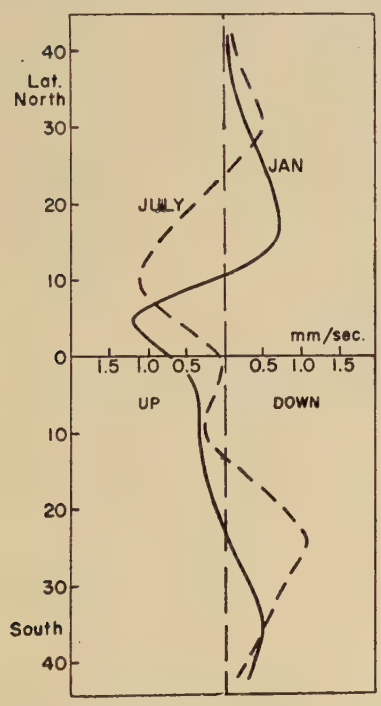

Figure 4. Net vertical motion (mm sec^{-1}) at 1 km in January and July.

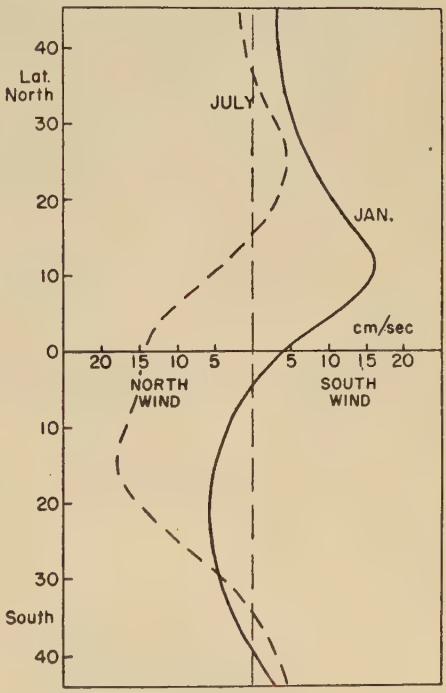

Figure 5. Net return flow between 1 and 13 km (cm sec^{-1}) in January and July.

Fig. 5 gives the speed of the mean return flow between 1 and 13 km, calculated under the assumption that the return flow vanishes at 13 km. Mass continuity demands that

$$\int_{0}^{1\text{km}} \text{div } (\rho v)\, dz + \int_{1\text{km}}^{13\text{km}} \text{div } (\rho v)\, dz = 0 .$$

Because of the assumptions previously stated,

$$\overline{\text{div } (\rho v)}_{(1\text{-}13 \text{ km})} = -\frac{1}{24} \text{div } (\rho v)_{\text{surface}} \quad . \quad . \quad . \quad (3)$$

This equation can be integrated numerically, if we set $\rho v = 0$ in the equatorial zone where $v = 0$, and use the density of the 500-mb level as mean density of the upper layer.

The pattern of Fig. 5 again must conform to that of Figs. 3-4. Of principal interest is the speed of the mean return flow. It attains a maximum of 16 cm sec^{-1} in the northern hemisphere and slightly more in the southern hemisphere. Its mean strength is 6-7 cm sec^{-1}. If it were possible to compute the return flow as a function of height, we should of course encounter layers where its speed is much larger.

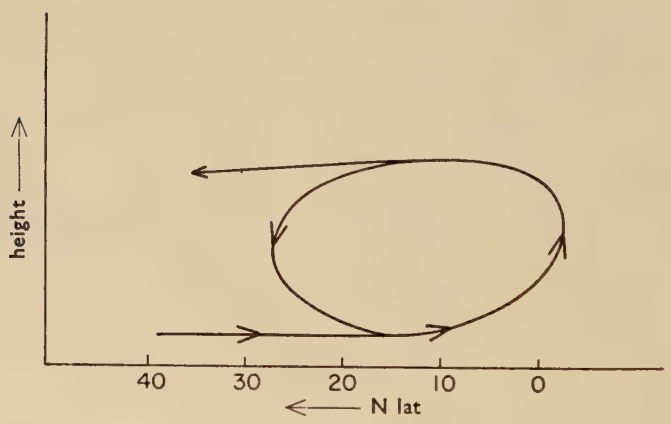

Figure 6. Mean circulation of lower latitudes in northern-hemisphere winter inferred from the computations.

5. Discussion

The question that has occupied meteorological literature to the present day is the role of the mean meridional circulation in maintaining the heat and momentum balance of the atmosphere. As shown recently (Riehl 1950), its strength is quite insufficient for maintaining vertical heat balance in low latitudes, even if we suppose

that the equatorward flow in the low levels extends through a much deeper layer than here assumed. We must fall back on vertical eddies to explain this aspect of the heat balance.

Following Defant (1921) and others, we also have to utilize the cyclones and anticyclones (troughs and ridges aloft) as large-scale turbulence elements to provide for lateral heat exchange. The meridional temperature gradient in the middle troposphere is about 1°C per 2° lat. between latitudes 20° N. and 70° N. in winter. If the meridional return flow is about 1/10° latitude day^{-1} (Fig. 5) and the radiational cooling aloft has the order of 1°C day^{-1}, then the return flow carries only 5 per cent of the heat necessary to obtain balance. If we raise the rate of return flow toward a maximum value (4 to 5 times that of Fig. 5), we still cannot account for more than a fraction of the meridional heat transfer by this means.

We encounter a different situation when considering momentum. The study of momentum transfer, begun by Jeffreys (1926), recently has been taken up by a wide group of meteorologists who have divergent view-points (*cf.* Starr 1948, Rossby and Starr 1949, Widger 1949, Palmén 1949). Some of the authors lean to the opinion that momentum transfer, similar to heat transfer, must be accomplished by eddy motion. Palmén, however, stresses that a mean return flow of only 6 cm sec^{-1} will produce the same amount of angular momentum transfer as that due to eddy motion computed by Widger (1949) at the latitude of maximum transfer. It is now apparent why we have been interested in lowest possible values of the return flow. We wanted to see whether 6 cm sec^{-1} could be a gross overestimate. We note, however, that even the average value of our minimum return flow, taken over all latitudes, is more than that. Without presuming to enter the discussion of the authors mentioned, we conclude that our computations favour Palmén. It follows that the mean meridional circulation must be considered in total angular momentum budgets. It does not follow, of course, that this circulation alone is responsible for momentum transfer.

In conclusion, we can ask to what extent our computations verify previous sketches of the meridional circulation cells, especially those of Rossby (1941) and Rossby and Willett (1948). Fig. 6 shows the portion of the mean circulation that we can actually infer from the computations. This sketch, of course, only outlines the net transfer of air and in no way indicates conditions to be encountered along individual meridians. Since, moreover, the hemispheres are asymmetrical and the seasonal variations large, Fig. 6 shall apply to the northern-hemisphere winter only.

A "direct" circulation cell exists in the tropics, but the multiple equatorial cell structure suggested by Rossby (1949) is missing. We should be able to find this structure if we constructed a regional profile for the central Pacific in July. The ascending motion in the equatorial belt — which reaches a maximum near 5°N. — already gives way to descent near 10°N. Downward motion extends from there to the limit of our profile but is strongest about 15-20°N. At high levels, therefore, only part of the northward-moving air reaches the polar zone. Another part sinks in the trade wind belt and returns toward the equator. Except for the

latitude of maximum descent, our picture corroborates the classical models in the tropical zone.

This agreement extends to the direction of transport of absolute angular momentum. It is well known that the equatorward-moving trades at the surface pick up angular momentum from the earth. Since the speed of the easterlies decreases with height in the average taken around the globe from at least 10° N. northward (Riehl 1950), upward flow of angular momentum can take place only near the equator. There the strength of the easterlies may not vary with height. From about latitude 10° N. poleward, absolute angular momentum is transported downward by the mean motion and by the eddy exchange of air between low and high troposphere. The surface easterlies gain momentum from above and below in the trade wind belt. Inflow of polar air with low angular momentum across the subtropical ridge-line provides for balance.

Acknowledgment

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The theory and use of upper air thickness patterns in forecasting

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Summary

The combination of the ordinary synoptic chart with the 1,000 — 500 mb thickness pattern, and the implied 500 mb contour chart, provides a first approximation to a three-dimensional representation of the troposphere. Although incomplete, the representation permits the introduction of dynamical and thermodynamical theory and provides a basis for scientific forecasting. The forecasting of thickness patterns, in effect of the temperature field, is a thermodynamical problem. The theory of advective, adiabatic and non-adiabatic temperature change is discussed. A useful approximation to advection is obtained by regarding the thickness lines as material lines embedded in the surface geostrophic wind field. Climatological monthly means and extremes of thickness are given ; these provide a practical framework to the forecast. The dynamical development is related with the geometry of the thickness patterns as indicating the vertical variation of vorticity transport. Attention is directed to the development field associated with thermal troughs and ridges, confluence and difluence, and certain combinations of these. When the dynamical development so produced sets up a circulation which by advection maintains or increases the thermal distortion in the same sense, the situation is self-maintaining or self-developing. The warm sector depression, the baroclinic anticyclone and the jet stream complex are examples of such systems. A step-by-step procedure of forecasting prebaratic and pre-thickness charts, which has been used in experimental four-day forecasts, is outlined.

1. Introduction

The introduction of regular upper air data into synoptic meteorology, adequate in many areas to provide a reasonable general picture of the three-dimensional pressure, temperature, humidity and circulation patterns in the troposphere has given rise to a flood of new knowledge, new techniques and new theory, the impact of which on professional forecasting has not been wholly beneficial. In place of the single series of synoptic charts, analysed by methods introduced a generation ago and eminently manageable by those long experienced with them, we are rather suddenly provided with more data than we can easily digest, represented on numerous upper air charts and aerological diagrams. The information does of course justify itself immediately as factual knowledge readily applicable to very short-range forecasting, where the element of analysis preponderates over the element of prediction, but when it is a question of determining the probable development of the synoptic situation as a whole for 24 hours or more ahead the benefit provided by this upper air knowledge is by no means so impressive, in routine forecasting, as might be expected.

The reason lies we believe in the absence of a coherent system of forecasting which will allow the new knowledge to be used systematically : there is so much

the forecaster can take into account that he hardly knows where to begin or what weight to assign to different factors — the perturbations of the tropopause, the jet streams at 300 mb, the flow patterns at 500 mb or 700 mb, the temperature fields and thickness patterns for various levels, the stability criteria, the topography of frontal and other surfaces.

We may hope that in due course inspiration will come and everything will fit into a single physical and dynamical problem to be solved by truly scientific methods but failing this we are justified in attempting to make progress by successive approximations. It is for this reason that we have set ourselves the task of first getting the utmost assistance from only one set of upper air isopleths, namely the 1,000 — 500 mb thickness pattern, which, combined with the surface pressure pattern, includes the 500 mb contours.

It is believed that the results will be valuable and above all practical, and that this method of building up a system of forecasting can be extended logically by introducing other factors at a later stage. Scientifically, any mode of attack is to be welcomed, but the state of the science is such that no set of rules has more than a statistical validity. Thus a multiplicity of sets of rules based on different techniques are consistent only in a statistical sense ; in any individual case they lead to contradiction and confusions and to the negation of system. Our object is rather to take one set only, as, so to speak, a first approximation, and later to improve by introducing the greater complexity which is at first deliberately excluded.

The choice of the 1,000 — 500 mb thickness pattern as the foundation of the first approximation has been explained elsewhere (Sutcliffe 1947, 1948). In brief, the field contains an indication of the temperature with the gradients and other features of the thermal patterns, it contains an indication of the variation of wind with height, and, together with the surface chart, of the velocity field, the momenta, vorticities and kinetic energies. The choice of 500 mb is to some extent arbitrary but is probably as good a choice as any available in practice at present. Too shallow a layer is not representative of the over-all features, too deep a layer introduces observational difficulties and the peculiarities of the tropopause ; on the whole 500 mb is a satisfactory compromise.

No claim is made to originality in recognizing the value of this parameter. When, at the Deutsche Seewarte in Germany, constant-pressure charts were first published regularly in 1934, the 500 mb relative topography was at once given prominence and, as is evident from Scherhag's recent and valuable text-book (1948), the Germans have seen no reason to amend their choice. Other countries have gradually come into line, and today, wherever aerological analysis is made, the 500 mb contours and thickness patterns are introduced with a greater or less degree of emphasis.

The present purpose is to formulate the forecasting problem in terms appropriate to the technique, to state the basic principles underlying the methods, to indicate the practical procedures as far as this can be done without dealing with numerous examples, and so to prepare the ground for further contributions arising from research now in hand.

2. An illustrative situation

The present paper deals with general principles, not their application to particular situations, but it will help to fix ideas if we begin with one illustration, sufficient to show the nature of the practical problem. Knowledge of the elements of constant pressure analysis is assumed.

The selected case is the period 28-31 January 1949, represented in the charts of Figs. 1, 2, 3, 4. The surface data of these charts are for 0600 and the upper air data for 0300 G.M.T. These are taken from routine working charts prepared in the Meteorological Office, Dunstable, and are representative of charts constructed twice daily. They include the usual uncertainties due to observational inadequacy and are little more than schematic for the Pacific sector from which area data received at Dunstable at present are few. But it may be accepted that the general run of the isopleths and the general features of the patterns are substantially correct, sufficiently so for our present purpose. The nature of the isopleths is stated in the captions.

In Fig. 1, for 28 January 1949, we note first an anticyclone in central and western America, within but mainly to the west of a pronounced thermal trough. Although this is broadly a cold anticyclone it is strongly baroclinic. Farther east, over the Great Lakes there is an extensive warm sector depression associated with a weak thermal ridge ; this depression lies in a strong thermal gradient, which, however, is markedly difluent over the western Atlantic where there is another pronounced thermal trough. To the east of this trough, near the Azores, is another low, and this again has thermal difluence to the east. From mid-Atlantic to north Norway there is a long SW. to NE. sweep of almost " straight " thickness lines with, embedded in it, a weak ridge of high pressure to west and north of the British Isles. To the north of Russia lies a large deep depression situated just upstream of the crest of the thermal ridge extending across the Baltic and the White Sea. Over western and central Europe there is an anticyclone associated with a typically distorted thermal pattern — a long warm tongue to the north, evidently carried in the southwesterly current, and a cold tongue to the south carried round in the easterlies.

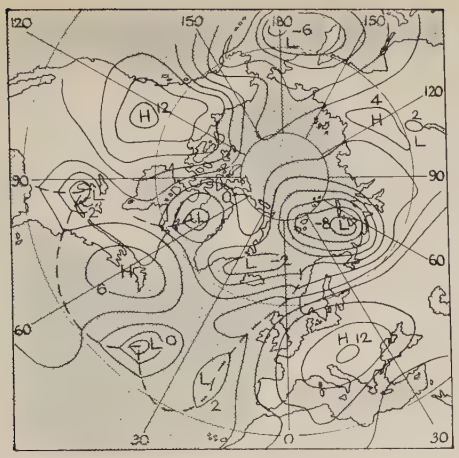
In Fig. 2 we see how this situation has developed during the first 24 hours of the period. Not much change has taken place over western and central America ; the large anticyclone has thrown out a ridge towards the south and south-east in the strong thermal gradient, but its centre remains to west of the thermal trough. The Great Lakes depression has moved to the Gulf of St. Lawrence, and the thermal ridge over its warm sector is still to be seen near Newfoundland. A strong gradient for northerly surface winds has been set up between this low and the Rockies anticyclone, and the effect of this is seen in the southward displacement of the thickness lines over central North America ; in consequence the axis of the main thermal trough over America has moved eastward. Off the east coast of America the southerly current has displaced the thickness lines northward intensifying the thermal ridge associated with the St. Lawrence depression, and sharpening the thermal trough on the west Atlantic. The low near the Azores has deepened

somewhat and moved eastward ; a thermal ridge now appears to east of this centre in about 25° to 30° W., and the thermal trough in mid-Atlantic has receded a little westward. Over Europe the large anticyclone is still the dominating feature and the pronounced distortion in the thickness lines, associated with it, persists. The warm air in the northern branch of this eddy has been carried far across Russia in the strong westerly current between the European high and the deep low over northwest Siberia. The shallow low which in Fig. 1 was situated westward of Spain and Biscay has evidently split into two parts. The first remains in its former position but no longer has a closed circulation, and its central pressure has risen. The other part, apparently a breakaway from the original system, has moved quickly NNE. in the strong thermal gradient and is now situated near the Faroes.

Fig. 3 shows the situation 24 hours later. The St. Lawrence depression, now off Labrador, has evidently assumed a controlling significance and a strong thermal trough has been brought down behind it although still leaving a trough in the Rockies region. The Azores depression, having become a cut-off system outside the main thermal gradient is now associated with a cold pool and the previous thermal trough from Greenland southward has almost disappeared. Very rapid warming has taken place in mid-Atlantic associated with advection from the south between the Canadian low and the European high. The depression centred near the Faroes on the previous day has moved to Scandinavia and deepened, and with the deepening a new thermal trough is forming behind it. The European anticyclone has retrogressed by building up a ridge from the British Isles to Greenland.

After another 24 hours the situation is as in Fig. 4. The depression from Labrador has moved to Davis Strait and is associated with a remarkable cyclonic distortion of the thermal pattern. The thermal trough has swung out over the ocean and Greenland is covered by the thermal ridge. The anticyclone persists over the British Isles and western Europe, with a ridge extending across the polar basin ; the anticyclonic distortion of the thickness pattern is again marked. A notable feature is the complete disappearance of the warm tongue and warm pools (represented in Fig. 2 (b) by the closed thickness lines for 18,000 feet) over Europe, leaving no air of such general high temperature nearer than north Africa and the central Atlantic. This is largely but not entirely due to the strong advection of cold air southwards over Scandinavia behind the now deep low over northwest Russia.

This period is remarkable for large changes in the circulation, one feature of which is the anticyclonic " blocking " over western Europe and the eastern Atlantic. The effect of the blocking is readily seen on comparing Figs. 1 and 4. On the former there is a continuous sweep of W. or SW. winds from near Iceland across Scandinavia into northwest Russia, and a SW. current over the British Isles merges into this general flow, the main anticyclone being situated over central Europe. In Fig. 4 the highest pressure is over southern England but an associated ridge extends to the polar basin. On each flank of this ridge the circulation is strongly meridional, and the W. to SW. air stream has disappeared completely. The phase of the thermal wave pattern over Europe and the eastern Atlantic changes con-



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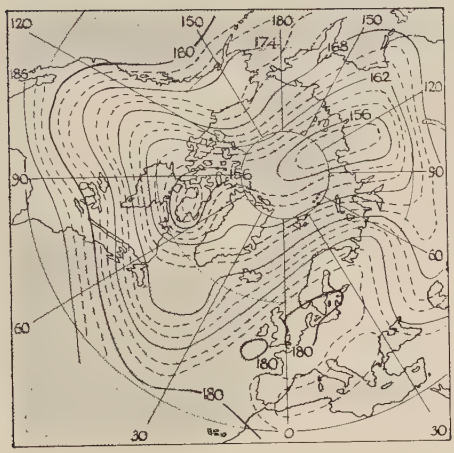

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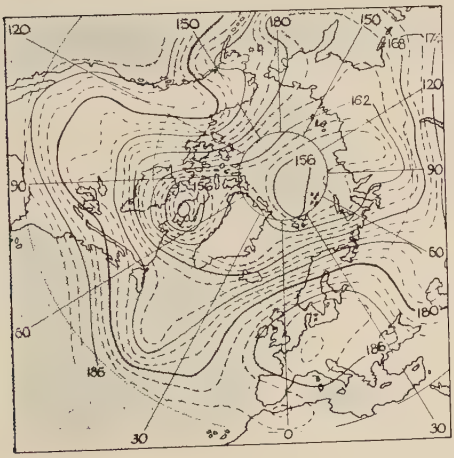

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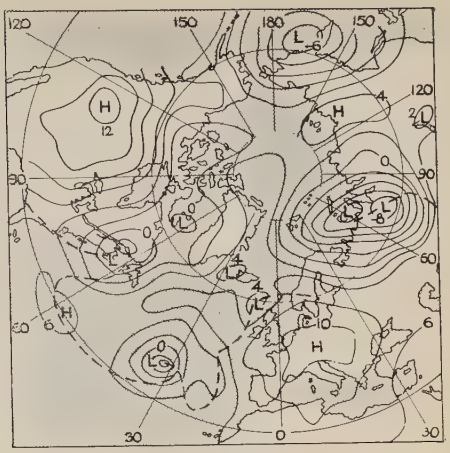
Figure 1. 28 January 1949



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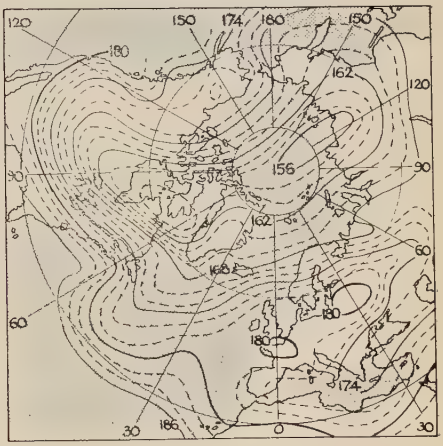

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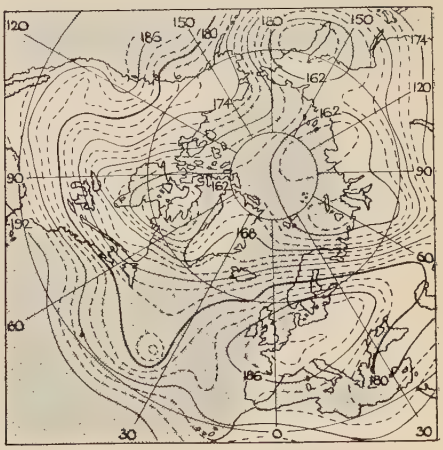
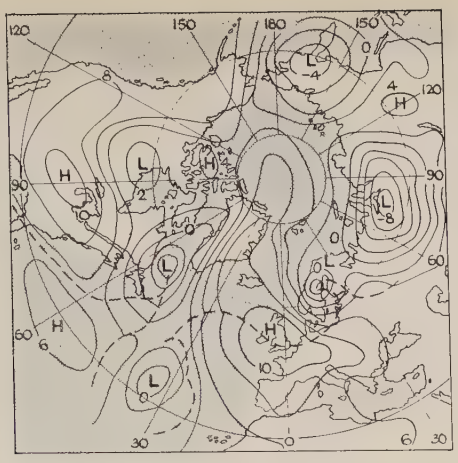


(c)

Figure 2. 29 January 1949

(a) Surface fronts and 1,000 mb contours
(b) 1,000 — 500 mb thickness
(c) 500 mb contours — unit 100 ft



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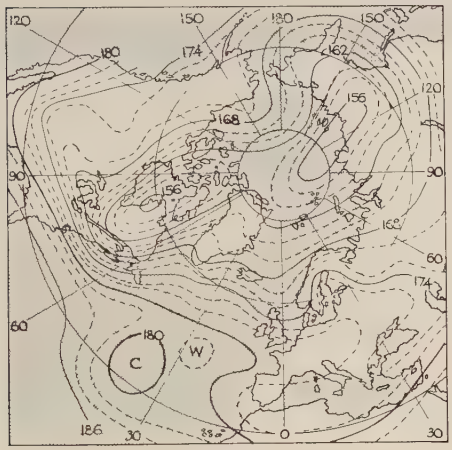

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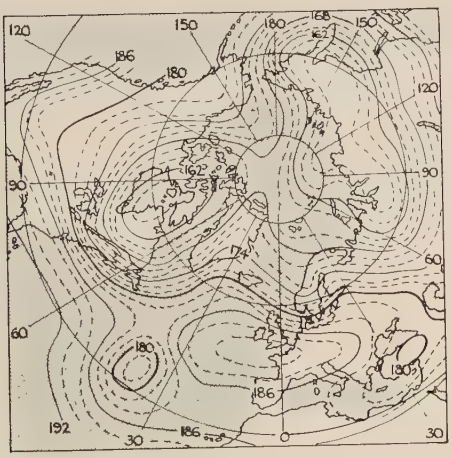
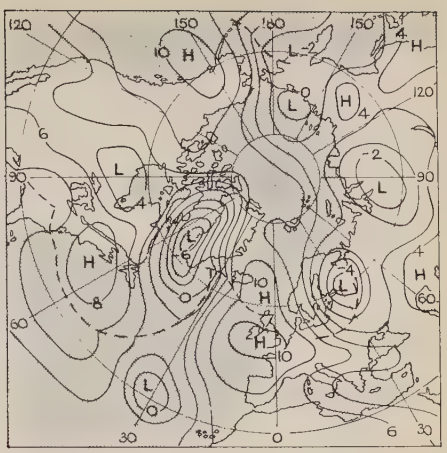


(c)

Figure 3. 30 January 1949



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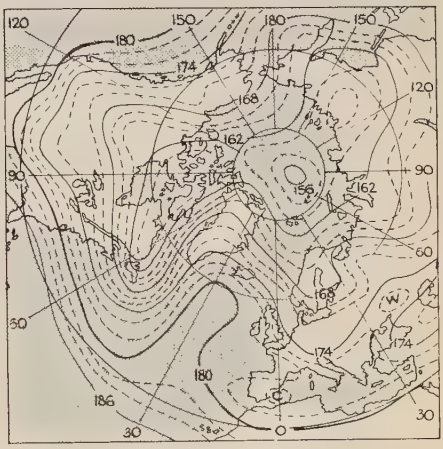

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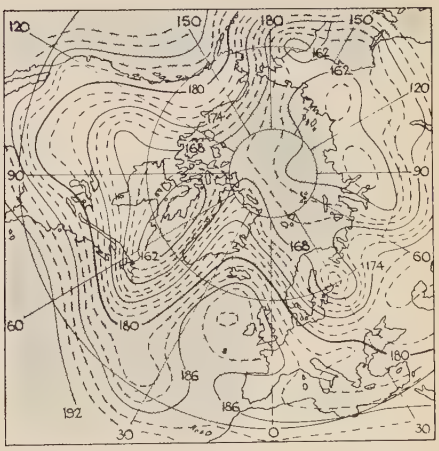


(c)

Figure 4. 31 January 1949

(a) Surface fronts and 1,000 mb contours
(b) 1,000 — 500 mb thickness
(c) 500 mb contours — unit 100 ft

siderably between these two charts, the ridge and trough system being displaced westwards ; in Fig. 1 (b), for example, the axis of the main thermal ridge lies from east of the Azores to the White Sea ; in Fig. 4 (b) from the Azores to east Greenland. It is clear, however, that this change of phase is due not to simple translation of the wave pattern, but to new formations. The wave length too alters considerably, as may be readily seen by noting the longitudes of intersection of the axes of the main thermal troughs and ridges with, say, the parallel of 60° N. latitude on the two charts.

The 500 mb contour charts show the development in a rather different way. The dominant features, the trough and ridge pattern, are clearly those of the thermal field modified usually only to a small degree by the surface pressure pattern. This is the normal situation, and whether we seek to diagnose development from the 500 mb contours using Rossby wave-length ideas and their extensions, or whether we stress the thickness pattern and use rather different criteria is not likely to be of major importance.

3. Formulation of the forecasting problem

Regarding the forecasting problem in the light of the chosen technique we have two sets of isopleths, the surface isobars or 1,000 mb contours (the difference between these is of no importance in the general problem) and the 1,000 — 500 mb thicknesses which by simple addition give the 500 mb contours as a third, but not independent, set.

As the situation develops, as from Fig. 1 to Fig. 2, both sets of isopleths are displaced and distorted and the problem of forecasting is essentially the construction of charts showing the forecast patterns of these isopleths. The fronts, included in the surface chart, are additional features which are changed and distorted in the development process and which may be lost by frontolysis or introduced by frontogenesis.

Since the selected parameters do not completely define the three-dimensional situation the physical problem is not completely formulated and no completely accurate prediction is theoretically possible. The forecast charts must therefore be liable to " probable errors." Although each forecast situation is of the same type as its predecessor and therefore, in principle, will permit the series to be extended indefinitely by the same techniques, the errors will accumulate and after some period the forecast situation will have no useful similarity with the actual situation which develops. The prediction must diverge from actuality and the useful period of a forecast will depend on the rapidity of this diverging. This sort of problem is however typical of natural science and weather forecasting differs not in kind but only in degree from other physical predictions.

Since the forecast charts, in common with the initial " actual " charts, define (albeit incompletely) the pressure and thermal fields and the main features of the flow patterns, the prediction must, implicitly or explicitly, take account of the dynamics of the flow and of the thermodynamics which controls the temperature

field. The method of attack seeks to combine dynamical with thermodynamical principles into a technique which by empiricism and experienced judgment can become an effective practical tool.

4. The theory of thickness changes

If the chosen technique has any claim to novelty in scientific emphasis this lies in the attempt to deal with the thickness patterns or fields of temperature in their own right and so, in principle, to bring thermodynamics into forecasting procedure. It is proper therefore to give first consideration to this aspect and, with some modification, the treatment follows that of Sutcliffe and Godart (1942) in an official memorandum not otherwise published.

If h is the geopotential thickness of the layer between constant pressure surfaces, p and p_0 and the other symbols have their conventional meanings

$$h = \int_p^{p_0} \frac{RT}{p}\, dp \qquad = R \int_p^{p_0} T \,.\, d \log p$$

and

$$\frac{\partial h}{\partial t} = R \int_p^{p_0} \frac{\partial T}{\partial t}\, d \log p \qquad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where the variables are taken as t, the time, x, y, horizontal cartesians, and p the pressure defining position in the vertical*. Partial derivatives have their usual meaning ; thus, *e.g.*, $\frac{\partial T}{\partial t}$ means the time rate of change of temperature at a point defined by constant x, y, p. (These variables were introduced in the technical memorandum referred to above and have been further explained by Sutcliffe (1947)).

If $\frac{d}{dt}$ signifies differentiation following the moving material particle we have

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{dx}{dt} \,.\, \frac{\partial}{\partial x} + \frac{dy}{dt} \,.\, \frac{\partial}{\partial y} + \frac{dp}{dt} \,.\, \frac{\partial}{\partial p}$$

or

$$\frac{\partial T}{\partial t} = \frac{dT}{dt} - u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} - \frac{dp}{dt} \frac{\partial T}{\partial p}$$

Also (Brunt 1941, pp. 38, 40)

$$\frac{dT}{dt} = \frac{1}{c_p} \frac{dq}{dt} + \frac{\gamma}{g\rho} \frac{dp}{dt} \qquad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and

$$\frac{\partial h}{\partial t} = R \int_p^{p_0} \left\{ -\left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) + \frac{dp}{dt} \left(\frac{\gamma}{g\rho} - \frac{\partial T}{\partial p} \right) + \frac{1}{c_p} \frac{dq}{dt} \right\} d \log p \quad . \quad (3)$$

where q is the heat energy per unit mass given to the element, c_p is the specific

* Strictly, the temperature T is the virtual temperature but it is very doubtful whether this refinement has any practical significance.

heat at constant pressure, and γ is the dry adiabatic lapse rate. The case of condensation with ascent is covered if γ_s, the saturated adiabatic lapse rate, is substituted for γ.

The local rate of change of thickness is therefore represented by the three terms on the right of Eq. (3), which are properly regarded as due to three distinct processes and may be represented by A (advective), D (dynamical) and N (non-adiabatic) where

$$\frac{\partial h}{\partial t} = A + D + N$$

(a) *The advective thickness tendency*

The advective term is

$$A = -R \int_p^{p_0} \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) d \log p$$

$$= - \left(u_m \frac{\partial}{\partial x} + v_m \frac{\partial}{\partial y} \right) h$$

where u_m, v_m are some mean values of the component velocities over the range of height.

This quantity may be thrown into various alternative forms.

Thus Sutcliffe and Godart effectively represent the vector wind $\mathbf{V}$ at any level by

$$\mathbf{V} = \mathbf{V}_{0g} + \mathbf{V}_{Tg} + \mathbf{V}_{ag}$$

where $\mathbf{V}_{0g}$ = 1,000 mb geostrophic wind

$\mathbf{V}_{Tg}$ = thermal (geostrophic) wind

$\mathbf{V}_{ag}$ = departure of the wind from the geostrophic — the ageostrophic wind

The advective thickness tendency has thus a component $-\mathbf{V}_{0g} \cdot \nabla h$ showing that the thickness lines tend to be advected with the 1,000 mb geostrophic wind. This is a very important contribution in many circumstances.

The second component, taking into account the thermal wind equation, is readily shown to be proportional to the area of the thermal wind hodograph over the range of height. If the thermal wind *direction* is uniform over the layer the area vanishes. In any case as we are deliberately confining our attention to two levels, 1,000 mb and 500 mb we have no basis for dealing with variations in thermal wind direction over the intermediate levels and the effect must be regarded as a finer point to be dealt with, at a later stage, by elaborating the technique. The third effect, due to advection by non-geostrophic motion, is, in the main, small compared with the geostrophic advection although certainly not always unimportant. But again we are limited by technique and by observational data ; ageostrophic components are not, in routine work, even approximately determinable in the free atmosphere and we can only proceed on the assumption that the effect will not usually be critical.

Thus an indication of the effect of advection in changing the thickness pattern is given by the surface geostrophic advection.

That this effect is regularly significant requires little demonstration ; the whole basis of frontal and air-mass methods rests on the fact that changes take place to a large extent by advection, with " air-mass modification " entering as an important control. Although in any particular case advection may have a greater or less importance and be more or less overshadowed by other processes there is no doubt that it must always be taken into account.

(b) *The dynamical thickness tendency*

The name " dynamical " is chosen as consistent with the use in meteorology of " dynamical heating " and " dynamical cooling " to describe the changes of temperature due to adiabatic compression and expansion associated primarily with subsidence and ascent.

In the form

$$D = R \int_{p}^{p_0} \left(\frac{\gamma}{g\rho} - \frac{\partial T}{\partial p} \right) \frac{dp}{dt} \cdot d \log p$$

the effect is due to dp/dt rather than to vertical motion strictly ; but this is thermodynamically sound and, as we have stated elsewhere, for many meteorological purposes we might do well to define " subsidence " by a positive value of dp/dt, " ascent " by a negative value. It is obvious that with subsidence, in this sense, the thickness increases always ; with ascent the thickness decreases, presuming a lapse-rate less than the adiabatic. By the definition of the saturated adiabatic lapse-rate, condensation is taken into account by substituting γ_s for γ in the above expression ; ascent then produces warming and an increase of thickness when the lapse rate exceeds the saturated adiabatic.

There is no doubt whatever, from evidence widely available in the texts, that warming by subsidence is often considerable. Petterssen and others (1947) give typical subsidence rates which should imply temperature changes averaging, up to 500 mb, about 1°C in 6 hours (their values are obtained from the observed isobaric temperature changes but they do not actually quote these). When prolonged this process may significantly distort the thickness patterns. Cooling due to ascent is less commonly mentioned but there is much synoptic evidence that dry and stable air masses are commonly subject to forced ascents associated with surface convergence and that the whole air column is cooled considerably in the process.

As regards the case of general warming and increase of thickness due to the ascent of a saturated air mass when the lapse rate is greater than the saturated adiabatic, it is observed that clear examples are not readily found from synoptic experience ; the required circumstances are the general ascent of an air mass which is saturated and unstable through a deep layer, circumstances which can hardly occur as the situation would have broken into deep convection cells at an earlier

stage. In large precipitation areas the lapse-rate is usually stable in the deep cloud masses, and in regions of convectional rain the upper air is usually far from saturated outside the local convection clouds. Thus over any region of general ascent the thickness up to 500 mb is likely to be reduced by the ascent.

(c) *The non-adiabatic heating processes*

Since in the heat economy of the atmosphere as a whole there is a net interchange of heat by advection between low and high latitudes, which balances the differential heating, ultimately by radiation to and from space, it is a fundamental necessity that the non-adiabatic processes of heating and cooling shall be of the same magnitude as the other processes : to treat the essentially balanced convectional circulation as adiabatic is an absurdity. This does not mean, of necessity, that small-scale disturbances cannot be treated as adiabatic but in so far as the circulations considered are essential to the general circulation of the atmosphere it is to be expected that non-adiabatic processes will be important. It is now generally believed that, in extratropical latitudes at least, the varying circulation patterns represented by synoptic charts are essential to the general circulation and indeed that there is no general circulation except in a statistical sense. If this is a correct belief it is to be expected that non-adiabatic processes will be as important as the others in determining the temperature and thickness patterns (and so the contour and pressure patterns) as they change from day to day.

There is ample synoptic evidence in support of this inference. It is sometimes stated that cold air masses moving to warmer regions are warmed mainly by subsidence, that warm air masses moving into colder regions are cooled by ascent or lifted entirely by frontal action. These processes are of course important but polar air masses may, in cyclonic circulations, penetrate to low latitudes with little or no subsidence, warm air masses may be advected far polewards or over the continents in winter without convergence, but there are very definite limits to the displacement of the thickness lines, which must be taken into account even in day-to-day forecasting.

Radiation has often been regarded as a slow process with little bearing on the short period problem but this now seems to be unsound. The rate of cooling of the atmosphere by radiation is estimated as from 1°C to 3°C per day and 3°C represents some 200 ft. in the thickness of the 1,000 — 500 mb layer. In determining the pattern this is comparable with about 7 mb in the surface pressure field and, while this does not represent a large " tendency " in highly active regions it would be of controlling importance over the field in general.

It would however be inappropriate here to attempt a mathematical treatment of transference of heat by turbulence and penetrative convection through the free atmosphere. It suffices to note that the heat gained at the surface is spread through the convective region, which in deep polar air may be the entire troposphere ; the latent heat liberated in precipitation is an important contribution. That the process is regularly significant is obvious from synoptic experience.

(d) *General remarks*

Theory and synoptic evidence are adequate to show that advective, dynamical and non-adiabatic processes are, in suitable circumstances, each liable to be significant and to contribute to the thickness tendency an amount equal to the mean thickness tendencies actually observed. While theory has made striking progress it is however not possible to calculate with any degree of accuracy the amount of heating, and the change in thickness, which will occur in a given air mass in a given locality, season of the year and synoptic situation. But there is ample scope for synoptic research, largely empirical but based on these physical principles, which will put the forecasting of thickness patterns on a much firmer footing than it is at present. Such research is in hand.

5. Climatological aids

Climatology in its wide sense includes all aspects of forecasting which depend on experience, whether these are presented in statistical form or remain as an unformulated body of empirical knowledge stored in the memory of the forecaster. A virtue of the thickness pattern technique is that it is more amenable in some respects to synoptic climatological treatment than are contour and flow patterns themselves — owing largely to its thermal implications and the physical controls on temperature change.

Any thickness line has a mean seasonal position, which can be represented by mean charts, and departure from the mean position is an immediate and significant indication that physical processes are operating to maintain the temperature anomalies. The analyst is therefore led to explain the anomaly and so to judge whether it will become aggravated, persist or relax.

The mean thickness chart also provides a direct measure of the mean thermal circulation index (analogous to a zonal index) for any region, and the anomaly pattern likewise gives an index anomaly as well as a generalised temperature anomaly. Studies of the variations from year to year and of persistent anomalies at any season have much promise as throwing light on climatic variations and long range forecasting.

The mean seasonal charts are therefore a tool of practical value and theoretical interest, with many applications, and should always be to hand in a forecasting laboratory.

The monthly mean positions of thickness lines for the three-year period October 1946 to September 1949, shown in Figs. 6 (a) to 17 (a) were obtained by straightforward use of the daily (0300 G.M.T.) thickness charts. The mean monthly thicknesses were calculated from the daily interpolated values at a fixed set of points, uniformly spaced on a square grid, but otherwise arbitrary. It is possible by continuity and scientific judgment to prepare reasonable charts every day even where data are missing, and so to avoid many of the difficulties which would arise by treating the average values at specific stations, and attempting to construct isopleths on the resulting network of values. In view of the short period

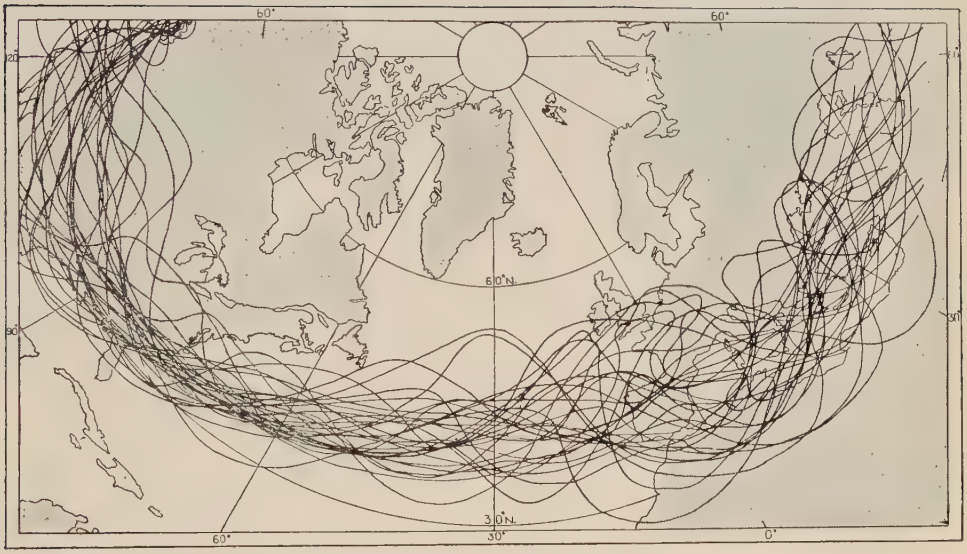
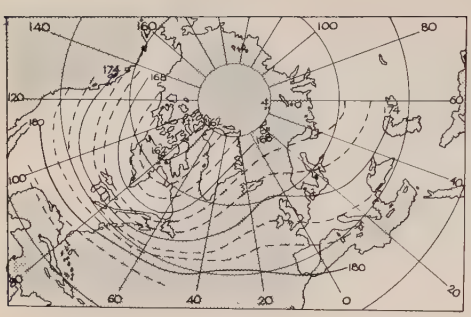
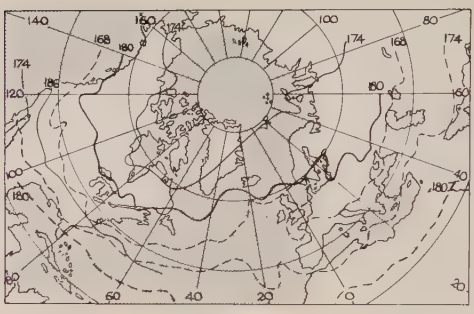
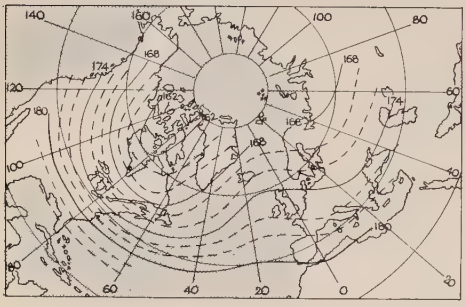


Figure 5. Composite chart of 18,000 ft. thickness line for each morning of January 1948.

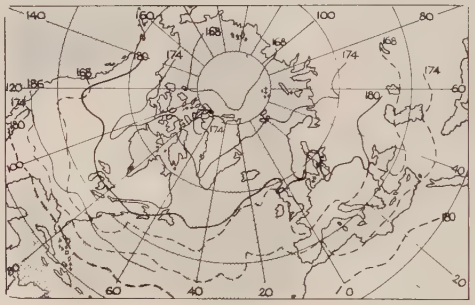


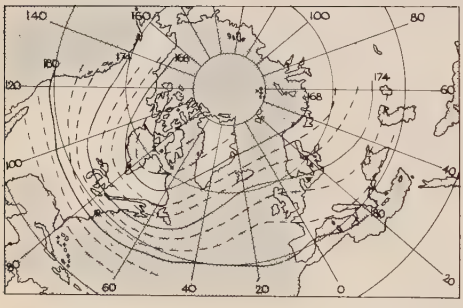
(a) Figure 6. January (b)



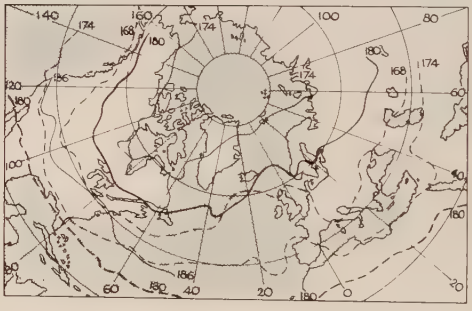


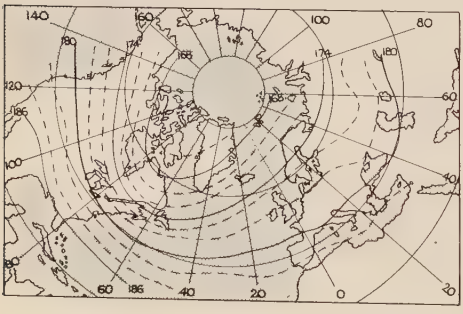
(a) Figure 7. February (b)



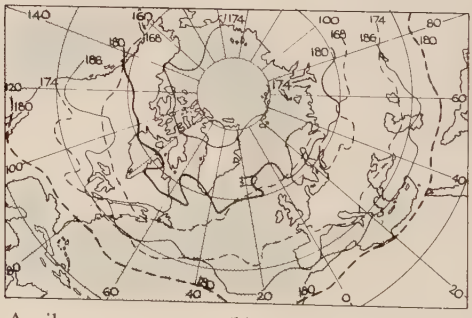


(a) Figure 8. March (b)



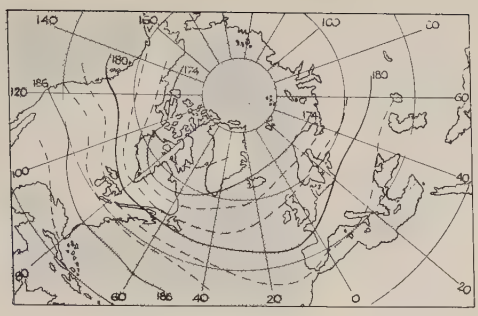


(a) Figure 9. April (b)

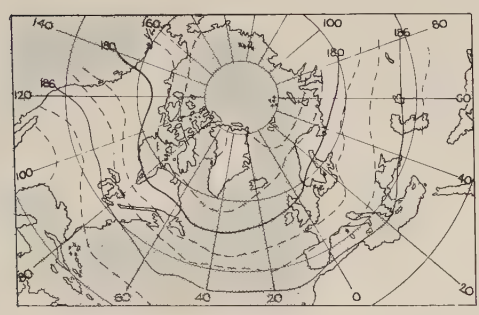


Thickness 1,000 — 500 mb, unit 100ft, period October 1946 — September 1949.

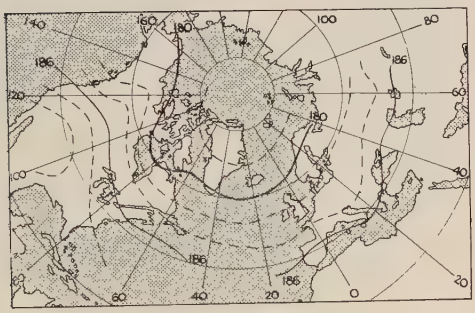
(a) monthly means
(b) maxima ————, minima — — — — —



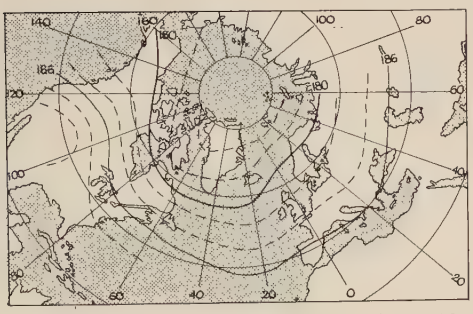
(a) Figure 10. May (b)



(a) Figure 11. June (b)



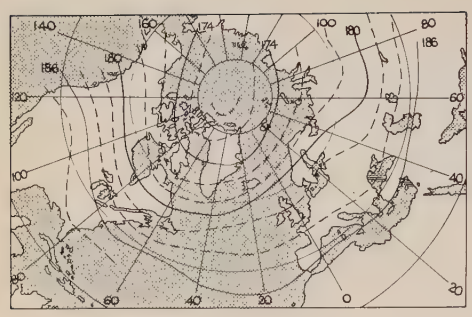
(a) Figure 12. July (b)



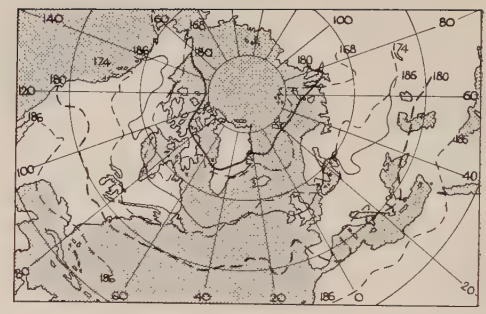
(a) Figure 13. August (b)

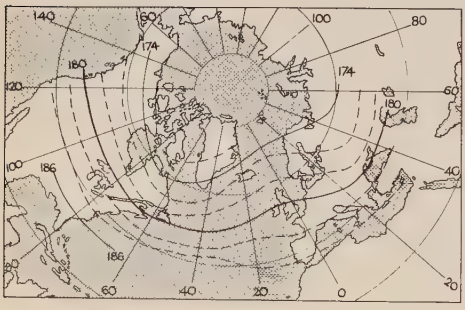
Thickness 1,000 — 500 mb, unit 100ft, period October 1946 — September 1949.

(a) monthly means
(b) maxima ————, minima — — — —

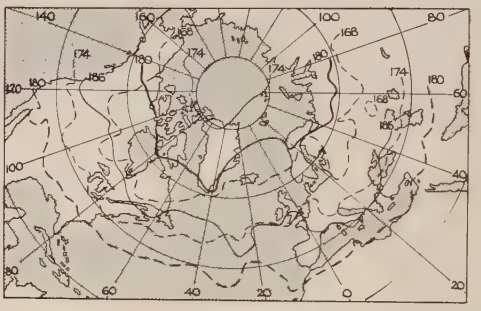


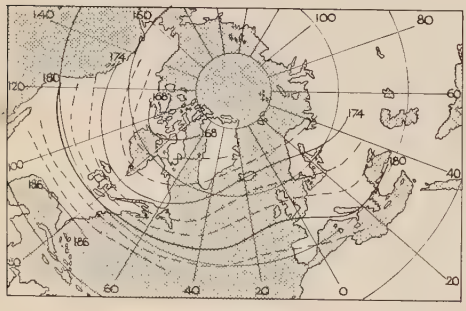
(a) Figure 14. September (b)



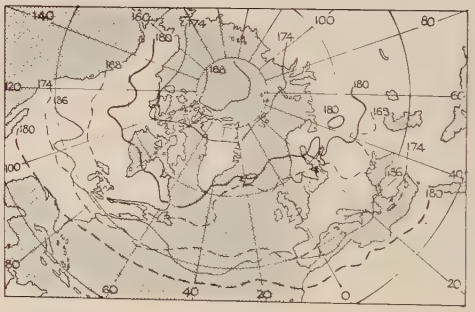


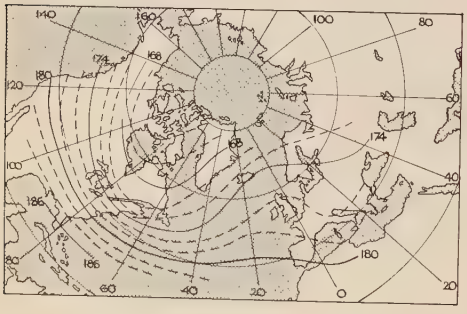
(a) Figure 15. October (b)



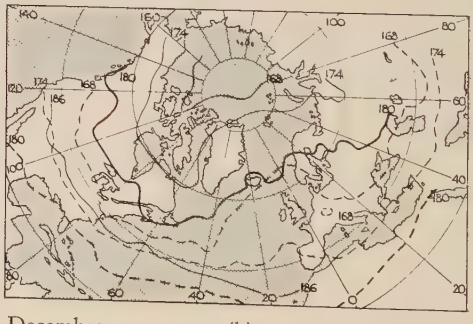


(a) Figure 16. November (b)





(a) Figure 17. December (b)



Thickness 1,000 — 500 mb, unit 100ft, period October 1946 — September 1949.

(a) monthly means
(b) maxima — ———, minima – – – –

involved, these charts do not, of course, provide a set of normals, but are still extremely useful, as the seasonal control is pronounced, and variations from year to year of the mean thickness appear to be considerably less than the variations of surface temperature, the patterns less variable than those of surface pressure.

Isopleths of the standard deviation would also be worth preparation but the computations have not yet been made, and for practical use composite diagrams such as Fig. 5, taken from a previous article (Sutcliffe 1948) are a ready aid in estimating the likelihood of any thickness line taking up an extreme position. By taking the northern and southern envelopes of the lines on such a composite diagram we arrive at a chart showing the extreme displacements, for the month, of the thickness line concerned. Combining the monthly envelopes we obtain charts, such as Figs. 6 — 17 (b), which show the extreme positions of certain standard thickness lines for each of the 12 months over the three-year period October 1946 — September 1949. In forecasting, these are used with the mean charts as indicating the possible departure from the normal position. With experience one may judge whether the synoptic conditions are such as will permit of extreme displacements, primarily by maintaining a strong advection to offset the climatic tendency to relax towards the norm.

The curves of extreme positions of thickness lines are characterised by numerous small bulges and loops ; these are to be expected in view of the way in which the lines have been constructed. Adjacent bulges may well represent extreme displacements on widely separated days, and there is no reason for smoothing them. Indeed the presence of a pronounced loop, such as in the 16,800 ft. thickness line over the British Isles and northern France in Fig. 6 (b) is usually an indication that the extreme displacement which it represents has been infrequent in the past, and should not be given undue weight in forecasting. These charts may obviously be regarded as showing maximum and minimum thicknesses respectively and for convenience they will be referred to as such.

Having regard to the distribution of mean temperature over the earth's surface it would be expected that the hemispherical mean thickness pattern should consist basically of curves enclosing low thickness values over the polar regions and lying along the parallels of latitude, but in fact distorted owing to the irregular heating of the earth's surface and the meridional transport of warm and cold air inherent in the general circulation. That the underlying pattern is of this simple type is evident at once from Figs. 6 (a) to 17 (a).

The main factor modifying this basic pattern is geographical ; the broad seasonal differences of temperature between land and sea surfaces, taken up by the overlying air, produce variations in the thickness isopleths similar to those in the monthly mean surface isotherms ; the mean thickness lines trend northward over sea and southward over land areas in winter and *vice versa* in summer. Thus a series of troughs and ridges is produced in the simple circumpolar pattern.

On the chart of mean thickness for January (Fig. 6 (a)) there is a broad thermal trough over the eastern half of North America, and another (shown incompletely on account of the lack of observations) over Siberia, where the lines show a pro-

nounced southward trend. On the NE. Atlantic, where the mean sea-surface temperature is abnormally high for the latitude, there is, as would be expected, a pronounced thermal ridge, and a ridge is also suggested over the NE. Pacific. The maximum and minimum thickness charts show characteristics similar to the means. All three charts indicate, for the same latitudes, generally colder air over N. America than over Europe. The chart of minimum thickness is particularly interesting as indicating the great southward sweeps of cold air to which N. America is liable ; the 16,800 ft thickness line there penetrates considerably farther south than in Europe, where doubtless it is held back partly on account of the warmth of the Mediterranean.

The same general features are reproduced in February and March, the most important change being the general increase of mean thickness between these two months over the land areas, due to the seasonal warming, and resulting in a decrease of amplitude of the broad trough and ridge pattern. The prominent northward bulge in the 17,400 ft thickness line over Hudson Bay and NW. Greenland on the maximum chart for February is due to an exceptional northward penetration of warm air on three days in February 1947.

In April the decrease of amplitude of the mean troughs and ridges continues, and the Atlantic ridge is no longer prominent. But the mean thickness lines running from WSW. to ENE. across the Atlantic still continue to follow approximately the mean sea surface isotherms. Over N. America the northward spread of the seasonal warming is well shown between March and April during which months the strongest mean thermal gradient is transferred from southward to northward of the parallel 40° N. No such effect is prominent in Europe, possibly on account of the slow warming of the Mediterranean.

During May and June the hemispherical warming proceeds rapidly, shown by the marked shrinking of the inner thickness lines and disappearance of some of them. This effect is still more marked in July and in that month, over the whole range, there are about only half as many thickness lines on the mean chart as in late winter. Exceptionally, over the eastern Atlantic and western Europe, warming between April and May proceeds only slowly as shown by the marked thermal trough on all three charts for May. In particular we notice the great southerly bulge in the thickness line for 17,400 ft over Spain, on the May minimum chart ; this is probably associated with the outbreaks of cold air over western Europe which are common in the early part of the month. During June the N. Atlantic thermal trough becomes established as a broad feature, which persists through July and August.

In the summer months there is a marked thermal ridge, on the mean charts, over N. America, its axis lying towards the west of that continent, and the run of the thickness lines near the west coast suggests that the Pacific trough is well marked, at least in the east. The weak thermal trough over eastern N. America in July is no doubt explained, to some extent at least, by the coldness of Hudson Bay, but the trough in the Urals area has no obvious thermal cause, and, in so far as it is not peculiar to the limited period on which these charts are based, it is

presumably of dynamical and advective origin.

From October to December the changes of the spring months, March to May, are seen in reverse and call for no special comment. On the whole, February is seen to be the month of lowest mean thickness but some localities are exceptional, at least for the three-year period considered. In SW. Iceland for example the lowest mean thickness, 17,200 ft persists from January to April, while at Vancouver Island it is 17,500 ft in December and January. The highest mean thickness occurs at most places in July with a tendency to carry over into August. Southern England appears to be peculiar with its highest mean thickness, 18,300 ft, occurring in July, August and September.

The range of thickness for any month can be readily seen from the maximum and minimum charts. The greatest monthly range, within the area covered by these charts, is about 1,800 ft indicated by the overlapping of the 16,800 and 18,600 ft lines on the minimum and maximum charts respectively. A range of this magnitude has been recorded in each month from January to May, inclusive, during which period it appears first in eastern U.S.A. but is gradually transferred to NW. Canada and Alaska. Exceptionally during the remaining months this range of thickness has also been recorded in September and October near Hudson Bay.

From experience with the daily charts it is apparent that the lowest thickness values of winter occur not over the geographical pole but in two separated regions, one of which, to the north of Canada, is clearly indicated also on the monthly mean charts, and the other lies over NE. Siberia. For the first two winters (1946-48) for which circumpolar thickness charts have been prepared the observations from Siberia were too scanty for the isopleths to be drawn there with confidence, and the intensity of the Siberian cold pole for those years is doubtful. More adequate observations in the winter 1948-49, however, permitted the circumpolar pattern to be completed on a number of occasions, and it appeared that, for this season at least, the cold pole north of Canada was often the main one. In any case it is evident that, in winter, the area of least thickness most frequently takes the shape of an elongated distorted oval, with its major axis lying from NE. Canada to NE. Siberia. The inner lines of the thickness pattern commonly delineate two cold troughs situated nearly opposite to one another with respect to the north pole. Farther out from the central region the pattern becomes more complex with the appearance of additional troughs and ridges, suggesting sometimes a three-fold or four-fold symmetry in the general wave pattern, in place of the simple two-fold symmetry of the innermost lines. In summer the tendency is for the cold pole to be situated near the geographical pole, and for the mean patterns to be rather more symmetrical than in winter, though, as mentioned above, geographical factors are still effective in producing distortions.

6. Dynamical principles

(a) *Basic ideas*

Studies of atmospheric dynamics on the synoptic scale have mainly been directed towards explaining idealised versions of what has been observed rather

than towards predicting development in real situations. Without entering upon a survey of the literature we may recognise that most of the significant work falls under the following heads :

(i) Perturbation theory — seeking to explain how and why depressions and anticyclones are initiated with their observed dimensions. For mathematical treatment idealisation is unavoidable and little has yet emerged which assists a practical forecaster in dealing with a current situation — except of course as fundamental background knowledge.

(ii) Theories of model depressions and anticyclones — which have co-ordinated the observed facts but have only to a small extent enabled the forecaster to deal more effectively with the real situation which is always so much more complex than the idealised models.

Amongst the more practical dynamical contributions it is fair to assign an important place to the long-wave theory and vorticity ideas derived from Rossby's work. There seems little doubt that valuable indications of the movement and deformation of the large-scale features can be obtained on this basis. Perhaps a very promising line is the recent application of vorticity ideas to computations on a field basis made by Charney and Eliassen (1949) although so far the method has only been applied in one dimension.

We shall not here attempt to deal with the techniques of application of these methods which have been discussed and developed elsewhere. Attention is confined to ideas and methods which have been developed independently, based on earlier theoretical studies (Sutcliffe 1939, 1947). That these ideas have much in common with those of Rossby and collaborators will be evident ; their main novelty lies in their application to the chosen thickness pattern technique.

Reference shoud be made to the quoted papers for a detailed justification of the methods but it is necessary to say something of the physical ideas. The atmosphere is a baroclinic fluid ; there is no better experience than that obtained from thickness patterns to drive this home. Even at 500 mb the thickness gradients, due to the thermal gradients, overwhelm the 1,000 mb contours to such an extent that the 500 mb contour pattern is in most of its features determined by the thickness pattern. At 300 mb this is even more striking. This obvious synoptic fact is also expressed by the well known high correlations between pressure and temperature in the troposphere and is, we believe, due to boundary conditions — probably frictional. Whatever the reason, it is a fact that an approximation to the high level flow on the broad scale would be given by assuming stagnation at the surface and taking only the thermal wind components. This is of course not always and everywhere true but the fact that it is broadly tenable proves that the circulation is essentially and dominantly controlled by the thermal patterns ; it is baroclinic.

We are therefore led to consider the three dimensional contour field as composed of two parts, the thermal field, determined by the baroclinicity, and the 1,000 mb contour pattern which appears equally at all levels. It is then proper to regard the flow of the atmosphere and the fields of horizontal divergence as expressing the adaptation of wind to the changing contour field and we may regard

this in its two parts ; first, the effect of adaptation to a field which changes uniformly at all heights and is shown by the development of the surface pressure features ; second, the effect of adaptation to the thermal (thickness) field which is flat and constant at the surface and increases its variability with height

A further implication of the relative constancy of surface pressure is that the vertical integral of horizontal divergence is approximately zero, a small resultant of possibly large effects of opposite sign at different heights. This important feature of atmospheric dynamics repeatedly stressed by Sutcliffe has also been emphasised by Charney (1948).

The three-dimensional distribution of horizontal divergence may therefore be divided into two parts whose vertical integrals are approximately equal and of opposite sign. The one is the field of divergence in the lowest layer appearing equally at all heights, the other the field having zero value at the surface and becoming more pronounced with increasing height being due mainly to the thermal wind field or thickness patterns.

It is evidently impossible to estimate directly the future magnitude of the constant part unless the development of the surface pressure field is known — and this it is desired to forecast. The method is therefore to attempt to deal with the variable thermal contribution which is given by the thermal field and its variation. Clearly this does not separate the contributions completely, for the thermal field, as we have seen, is modified by kinematical and dynamical as well as thermodynamical processes, but methods may be evolved for dealing with these difficulties.

If we write div $\mathbf{V}_0$ for the surface (isobaric) divergence, div $\mathbf{V}$ at any height may be written

$$\mathrm{div}\mathbf{V} = \mathrm{div}\mathbf{V}_0 + \mathrm{div}\mathbf{V}'$$

Integrating vertically we see that

$$\int_0^{p_0} \mathrm{div}\mathbf{V}\, dp = \int_0^{p_0} \mathrm{div}\mathbf{V}_0\, dp + \int_0^{p_0} \mathrm{div}\mathbf{V}'\, dp \simeq 0$$

or

$$\mathrm{div}\mathbf{V}_0 \simeq -\frac{1}{p_0}\int_0^{p_0} \mathrm{div}\mathbf{V}'\, dp = -(\mathrm{div}\mathbf{V}')_m$$

where $\mathbf{V}'$ is the shear wind, approximately the thermal wind, and suffix m indicates a pressure mean value.

Now the field of divergence of the thermal wind will in general have a similar horizontal distribution at all heights and will become more intense with height. We may therefore expect that the value at some suitable upper level such as 500 mb will be a good measure of the mean value and that the field of $(-\mathrm{div}\,\mathbf{V}')_{500}$ will be similar to the field of div $\mathbf{V}_0$ which it is required to estimate in the development problem.

It would of course be preferable to deal not with the value of div $\mathbf{V}'$ at one level as a representative parameter but with the vertical integral quantitatively

although it remains to be proved that the extra theoretical accuracy is of practical value.

Using certain approximations based on the vorticity theorem we have arrived at the following expression for the divergence of the thermal wind.

$$\mathrm{div}\mathbf{V}' = -\frac{1}{l} V' \frac{\partial}{\partial s} (\zeta_0 + \zeta + l) = -\frac{1}{l} V' \frac{\partial}{\partial s} (2\,\zeta_0 + \zeta' + l)$$

where $\frac{\partial}{\partial s}$ represents differentiation along the thickness line, ζ, ζ_0, ζ' are the vertical components of the vorticities of $\mathbf{V}$, $\mathbf{V}_0$, $\mathbf{V}'$ and l is the Coriolis parameter. The study of the distribution of this quantity at 500 mb gives the indication of the surface development.

The formula takes no account of the non-adiabatic changes in the thermal pattern. These are important at least in certain geographical areas and can be allowed for empirically. It also takes no account of thermal changes due to vertical motion. These promote cooling over a surface convergence area and warming over a surface divergence area, creating thermal fields which oppose the development. They therefore represent the damping effects of vertical stability and may again be allowed for empirically.

The formula does however give useful indications and, as has been shown, accounts well for " thermal steering " and many developmental thermal patterns.

If the variation in the thermal vorticity is relatively small, as with sensibly straight and parallel thickness lines, the development is controlled by $V' \frac{\partial}{\partial s} \zeta_0$ showing that a centre of surface vorticity tends to develop in the direction of the thermal wind with a speed proportional to V'. But the complications are great, the variation of the vorticity of the thermal wind is rarely negligible and the modifications due to stability control and other processes are such that the speed of displacement by thermal steering is at present best determined empirically by experience or statistical averages, and by judging the relative importance of steering and the other development processes. Certainly if all depressions, or all anticyclones, are considered together, there is no reason whatever to expect more than a fair correlation between movement and thermal wind over the centre, and the indiscriminate use of the steering principle, ignoring other development aspects, only brings disrepute to attempts to introduce dynamical ideas into forecasting.

Attempts are being made to deal with the thermal pattern on a field basis but observational difficulties intrude and at present the thermal development effect is estimated only by inspection in those parts of the pattern which have striking features of vorticity variation, regions of variable curvature and variable shear, particularly the neighbourhood of marked thermal troughs and ridges and the confluent and difluent areas associated with strong thermal gradients. It is most important to notice that the strength of the thermal wind enters not only directly but also indirectly in that the vorticity is usually large where the wind is strong. Thus development is most marked primarily in the regions of strong thermal wind.

The subject is an extensive one and will be elaborated elsewhere. We must be content here to present a few rules which, in the hands of an experienced synoptician, are useful

(b) *Some selected patterns*

(i) *The cold thermal trough — Fig.* 18 (*a*)

The cold trough is a common feature. It is associated with upper divergence and surface convergence (cyclogenesis marked C in the diagrams) ahead of the trough and upper convergence with surface divergence (anticyclogenesis marked A in the diagrams) behind. Apart from the tendency for new features to develop in accord with the rules, travelling pressure features tend to intensify or decline as would be inferred. That is, a depression travelling through the pattern (by thermal steering) will run readily across the trough to intensify at C while a travelling anticyclone or ridge will not readily pass the trough line and is liable to intensify at A. The mutual interaction of pre-existing cold trough and travelling pressure perturbation is of course important. An anticyclone at A and/or a cyclone at C produce circulations which by advection maintain or accentuate the thermal trough and the situation has a self-maintaining or self-aggravating character. Out-of-phase associations, by contrast, are quickly resolved and cannot long persist.

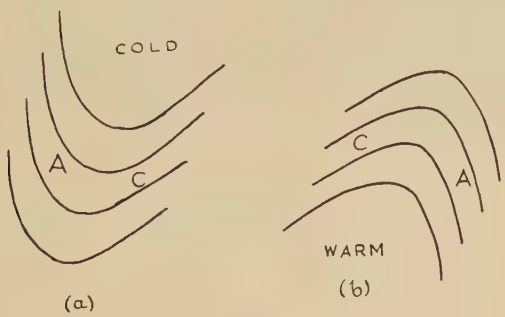


Figure 18. (a) The cold thermal trough ; (b) The warm thermal ridge. Cyclonic development, C, occurs forward of the thermal trough, behind the thermal ridge ; anticyclonic development, A, on the opposite sides.

(ii) *The warm thermal ridge — Fig.* 18 (*b*)

As the complement of the trough pattern, the development features may be inferred without further discussion. Probably the cyclogenetic post-ridge situation is less well known than the pre-trough situation but it is important. The pre-ridge anticyclogenesis corresponds with the building and maintenance of the warm anticyclone whereas the post-trough A of Fig. 18 (a) typifies the subsiding cold air mass.

(iii) *The sinusoidal thermal pattern — Fig.* 19

The sinusoidal pattern is essentially a combination of trough and ridge. It is the pattern of the classical warm-sector depression and cold anticyclone and

the C and A regions are immediately inferred from the above. Thermal steering is usually dominant and the situation travels in a wave-like manner.

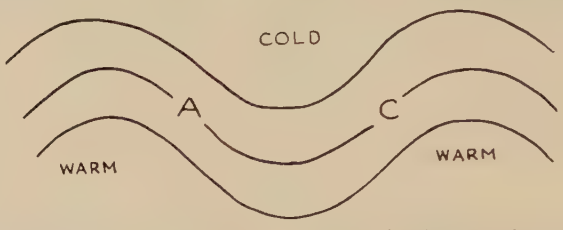


Figure 19. The sinusoidal thermal pattern. Cyclonic development is centred at the pre-trough inflexion, anticyclonic at the pre-ridge inflexion. With small amplitude wave-form, thermal steering is dominant and the situation travels in a wave-like manner.

(iv) *The cyclonic thermal involution — Fig.* 20 (*a*)

The cyclonic thermal involution is an exaggerated form of the sinusoidal and develops therefrom in the earlier stages of cyclonic occlusion. The reversed thermal gradient over the cyclonic region is however not in harmony with wave-like thermal steering and the situation is liable to evolve further with little movement.

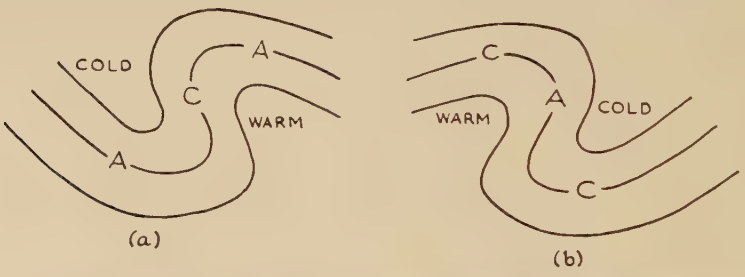


Figure 20. (a) The cyclonic involution ; (b) The anticyclonic involution. These patterns are distortions of the sinusoidal perturbations usually produced by depressions or anticyclones in the appropriate development regions. They are self-developing.

(v) *The anticyclonic thermal involution — Fig.* 20 (*b*)

This complementary sinusoidal involution is similarly the pattern of the well-developed and slow moving anticyclonic cell.

(vi) *The difluent thermal jet — Fig.* 21 (*a*)

Thermal difluence and confluence are of necessity associated with more or less well marked regions of concentrated gradient and it is convenient to use the term "jet" without implying any specially strong gradient. In the region of strong gradient the vorticity (due to shear) is cyclonic on the cold side, anticyclonic on the warm side and, as with the opening gradient the vorticity falls off, the anti-cyclonic A and cyclonic C regions are tolerably easily picked out. Again it is remarked that pressure systems travelling as they so often do in the strong thermal are so affected that cyclones swing out of the jet to the left, anticyclones to the right, and with little shear to carry them out of the region they may then slow down markedly.

Figure 21. (a) The difluent thermal jet ; (b) The confluent thermal jet. Cyclonic development is a feature of the left exit and right entrance of the thermal jet, anticyclonic development on the opposite sides.

(vii) *The confluent thermal jet — Fig. 21 (b)*

The A and C regions are shown in the diagrams to the left and right of the entrance to the jet. Travelling pressure features are however highly liable to break away from the jet entrance and run through the strong gradient to be replaced by new developments.

(viii) *The difluent thermal ridge — Fig. 22 (a)*

The combinations of curvature and shear variations are numerous but the four cases of thermal ridge and trough situations with either confluence or difluence are often recognisable and important. The situation is represented ideally in Fig. 22 (a) where the essential points are that the pre-ridge anticyclogenesis is thrown to the right, the post-ridge cyclogenesis to the left. Thus anticyclones do not tend to build up across the upper stream but keep to the warm side and the surface circulation so set up tends to extend the difluence forward. With weak thermals ahead there is little tendency for pressure systems to break and run through the pattern.

(ix) *The confluent thermal ridge — Fig. 22 (b)*

Here the pre-ridge anticyclogenesis is to the cold side with the post ridge cyclogenesis to the warm side. The surface circulation so set up tends to prevent the forward movement of the thermal ridge and even to cause it to become retrograde. The strong thermal ahead is however favourable for pressure features to break away and run through the thermal pattern rapidly. This is a notoriously difficult pattern to deal with in forecasting. Anticyclogenesis to the north and cyclogenesis to the south are symptoms of " blocking " in the westerlies, while the break-away features through the strong gradient are often critical points in short-period forecasting. The thermal field may be associated with break-away secondary depressions on warm fronts and warm occlusions. These have been specially studied by Sawyer (1950).

(x) *The difluent thermal trough — Fig. 22 (c)*

The combination of thermal difluence with the trough is probably the most certain indication of cyclogenesis on the cold side, at C in the figure. Anticyclonic development is most likely behind the trough on the warm side. The advection set up by such pressure features tends to carry the cold trough forwards but, with

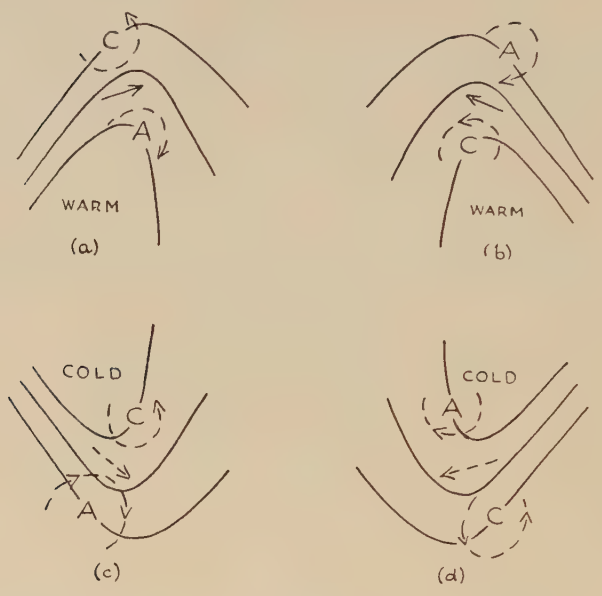


Figure 22. Combinations of thermal ridge and trough with difluence and confluence. (a) The difluent thermal ridge ; (b) The confluent thermal ridge ; (c) The difluent thermal trough ; (d) The confluent thermal trough. See text for descriptive comment.

light thermals ahead, the pressure systems do not readily break away from the thermal feature and the depression may deepen greatly with slow movement. It is to be noted that while the situation often evolves to a slow-moving cold occluded depression this is to the cold side of the main thermal gradient. Neither blocking of the westerlies nor a large cold outbreak into low latitudes readily evolves from this situation.

(xi) *The confluent thermal trough — Fig. 22 (d)*

With the strong thermal gradient ahead of the thermal trough cyclonic development is favoured on the warm side ahead of the trough with anticyclonic development to the cold side. The blocking tendency due to surface easterlies is important and the thermal trough moves slowly or becomes retrograde. Break-away depressions running in the strong thermals from the C-region are common but the situation is, like (ix) above, difficult to deal with. Cold air is liable to break through behind the cyclonic region into low latitudes and a cold cut-off depression south of the main westerlies may result. The anticyclonic development in the cold air near and behind the confluent cold trough is liable to be of much importance. There is regularly a dilemma in forecasting, whether a cold ridge will or will not develop well into the cold air behind a cold trough, and the difference between the difluent and confluent trough can be decisive.

If a thermal trough is markedly confluent cyclonic activity is most pronounced on the warm side forward of the trough line and anticyclonic on the cold side to

the rear. The tendency for cyclonic activity, which is so frequently associated with the difluent thermal trough, to pass to the warm side of the confluent trough so permitting anticyclonic development to the colder side, usually to higher latitudes, is a possible explanation of certain cases of unpredicted ridge building well into the cold air even across the cold trough. As in other complex cases confluence and difluence effects may be overlooked in the trough ridge patterns.

(c) *Self-maintaining and self-destroying systems*

Experience with thickness pattern techniques leads to a characteristic attitude to the synoptic problem. The analyst starts with a complex developing field, never with the idealised symmetry of perturbation theory, and tends to think of two processes, the dynamical development of the field of flow and the associated distortion of the field of temperature, mutually interacting. Although the interactions are complex some of the important aspects can be dealt with and it is possible to recognise situations which are self-maintaining and therefore persistent and others which are self-destroying and therefore non-persistent. It is of course natural that the self-maintaining systems are common or " typical," the others more unusual, but as forecasting failures are due more to the exceptional than to the typical situation the importance is not a matter of frequency.

(i) *The classical warm-sector depression — Fig. 23 (a)*

This is perhaps the best example of the self-maintaining, self-developmental system and is that dealt with in most perturbation theory. From our point of view it is interesting to note that the circulation of the depression creates the sinusoidal thermal pattern by advection and so produces a thermal field which in turn requires cyclogenesis at the trough-ridge thermal inflexion (see Section 6 (b) (iii)). The process appears self-evident and there is a ready-made explanation of the development of depressions which is perhaps more easily understood than any of the current and rather closely argued " theories," although it has of course much in common with the Bjerknes-Holmboe (1944) ideas. The eventual occluding by continued distortion coupled with dynamical cooling due to the development as represented in Fig. 23 (a) works out naturally if only qualitatively. In dealing with an individual depression we can watch and attempt to predict the individual thermal structure and are not dependent on gross generalisations. In special circumstances the development area may be quite non-typical and special treatment is possible.

(ii) *The classical mobile high*

The anticyclonic development between classical depressions appears as the mere counterpart of the depressions. The thermal distortion due to the circulation produces the necessary thermal pattern for the development and in favourable circumstances a process entirely analogous with occlusion goes through to completion with the warm anticyclone as the end product as represented in Fig. 23 (b) ; the situation is self-developmental.

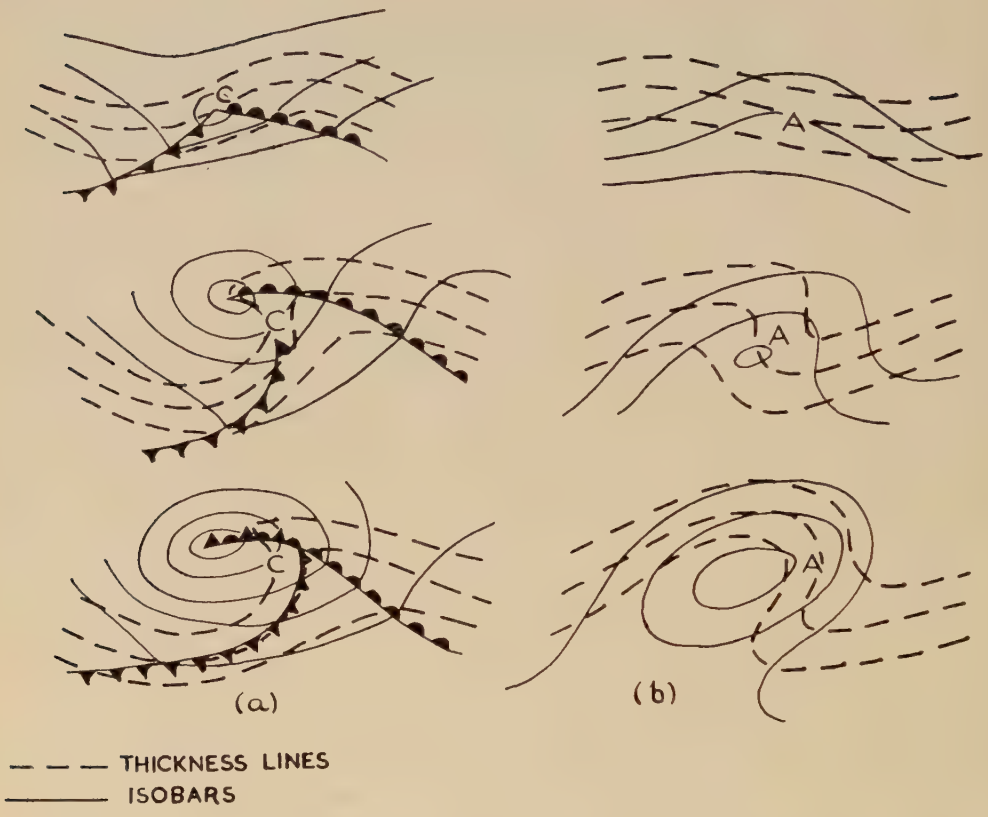


Figure 23. (a) Development of the classical warm-sector depression. The cyclonic development due to the thermal development process at C, favours the continuous distortion of the pattern. Cooling by ascent, the occluding process, leads to a cold depression. (b) Development of the baroclinic anticyclone shown as similar to that of the warm-sector depression, with anticyclonic thermal development leading to continued distortion of the pattern. Warming by subsidence leads to a warm anticyclone.

(iii) *The jet stream complex*

As indicated in Fig. 21 (a) the difluence at the outflow from a thermal jet favours cyclonic development to the left and anticyclonic to the right. If a depression and anticyclone appear here the advection tends to close the thickness lines together at the outflow and open them out further ahead so maintaining the difluence and extending it forwards. The complementary low-level circulations riding the mouth of the jet as it progresses forward form a self-generating complex of some importance. If this is combined with the jet entrance as in Fig. 21 (b), we see the frontogenetic hyperbolic region of Fig. 24 as a self-generating complex, dynamically and thermally. Jet streams develop in certain localities because the dynamical system which produces them is a self-developing complex.

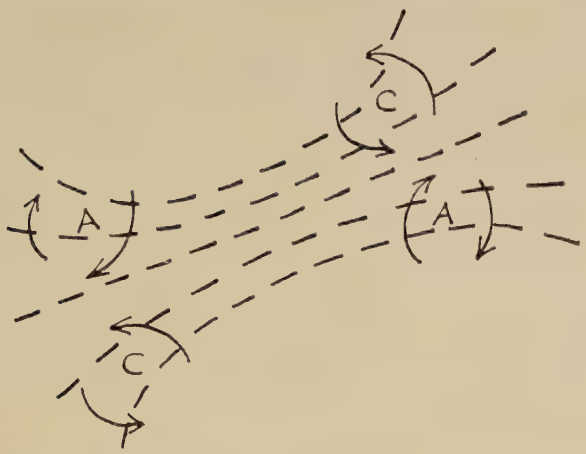


Figure 24. The thermal jet complex. The development regions favour the existence of depressions in the C regions and anticyclones in the A regions, which tend to distort the thermal pattern by advection and maintain or develop the jet structure. This is the hyperbolic frontogenetic complex which is self-developing.

(iv) *Self-destroying systems*

The circulation of highs and lows is such that the thermal pattern directly produced by advection usually favours the development dynamically. It is however possible in the complexity of nature for a low or high to find itself in a thermal pattern which does not support its existence and the situation must be rapidly resolved. These situations have however not yet been studied systematically.

(d) *Barotropic systems*

When the isobaric and isothermal surfaces coincide there is no thickness gradient and nothing emerges either from the technique or the theoretical approach adopted. The situation is non-developmental. It is not suggested that barotropic wave disturbances are impossible in the atmosphere on the synoptic scale but synoptic experience would not lead one to look for them. The long waves, at least in extra-tropical latitudes, are quite certainly baroclinic in the sense that the dominant term in the upper air motion is the thermal wind varying with height ; it is not a solid current, even approximately. This observed fact, coupled with the further fact that regions without thermal gradients tend to become stagnant anticyclonic or cyclonic cells, encourages the belief that the active dynamical systems of both small and large scale may be studied by the thickness technique as thermally controlled systems.

It is however believed that, while the active development is baroclinic and controlled by the thermal gradients, there are consequential changes which may be regarded as barotropic. Thus, for example, when a major depression develops there is a net loss of air from the region and this is not usually taken up entirely by the baroclinic ridges in the vicinity but seems to be spread over a very wide

area. The essential compensation is reasonably regarded as a barotropic disturbance perhaps in the form of a wave-like spreading through a wide environment. Synoptic experience supports this view for there is a clear tendency for the regions of flat thermal gradient to become anticyclonic and for high pressure to build or be maintained in these regions. Especially favoured localities are the polar and sub-tropical regions where the developmental thermal patterns are often very weak. In these regions, development, in the sense of active subsidence, may be truly very weak and the barotropic accumulation of air needs only to be sufficient to replace the frictional loss to maintain the cell. Little attention seems to have been given to this necessary compensation somewhere to balance the local losses or gains of air in the baroclinic developments although it must be of great importance in defining the large-scale pressure field. To incorporate the process into forecasting technique will obviously be difficult but the maintained slow surges of pressure over wide areas, although they produce no pronounced isallobaric field and no divergence-convergence field of any short-term significance, are of great importance in producing type changes over several days.

(e) *The effect of the variation of l, the Coriolis parameter*

For smaller-scale development the variation of the Coriolis parameter in the basic vorticity equation is small compared with the variation of the vorticity relative to the earth but for larger-scale developments it cannot be ignored. In the thermal development equation the significant differential factor due to shear is $(\zeta' + l)$ or the absolute vorticity of the thermal wind, and it is clear that development is closely related with the Rossby long-wave theory (1939, 1940).

There is however a difference if we are correct in stating that the long waves are primarily baroclinic. For a stationary non-developing long wave the quantity $V' \frac{\partial}{\partial s}(\zeta' + l)$ must vanish, and this leads, for a sinusoidal wave form, to the "stationary wave length" of Rossby. In order to make the argument clear it is convenient to explain this conception with a simple diagram, Fig. 25. The full line represents a sinusoidal stream line. At R, the ridge, there is anticyclonic vorticity due to curvature, at T the trough, this vorticity is cyclonic whereas at I, the inflexion,

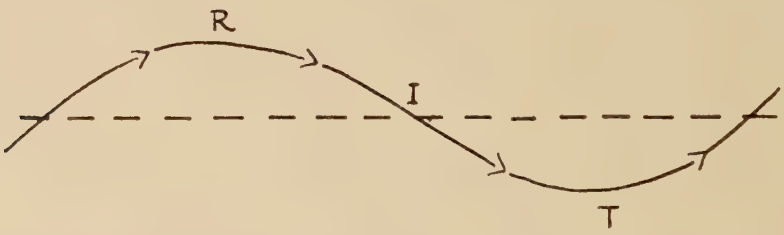


Figure 25. Illustrating the conception, due to Rossby, of a non-developing wave-form of stationary wave length when the variation in vorticity due to curvature is balanced by the variation in Coriolis parameter.

there is no curvature contribution. As however the Coriolis parameter is greater at R than at T it is possible for the two effects to balance and for the absolute vorticity to be constant and equal to l at the inflexion. We need not consider here what departure from a sine curve is necessary for complete uniformity. Since the curvature vorticity increases proportionately with the wind speed whereas the range of l depends only on the amplitude it is clear that the stationary wave length increases with the velocity and Rossby's formula gives

$$L = 2\pi/\sqrt{(U/\beta)}$$

where L is the stationary wave length, U the velocity and $\beta = \frac{\partial}{r\partial\phi}(2\omega \sin\phi)$ $= 2\omega \cos\phi/r$, in which r is the earth's radius.

Applying this idea to our baroclinic development equation it is seen that the relative divergence at any level represented by $V' \frac{\partial}{\partial s}(l + \zeta')$ cannot, with a given thermal wave form, have a stationary value at more than one level since V' (and ζ') increase steadily with height. At lower levels than that of the stationary value the wave length is too long, at higher levels too short and the consequential divergences above and below the level will be of opposite sign. It is evidently possible to have a situation in which the vertical integral of this divergence vanishes so that there is no resultant surface development. Such a situation might be taken to define a stationary wave length for the baroclinic wave which would be the value at the "level of non-divergence" said by Charney (1947) to be about 600 mb. To this extent the Rossby wave length formula might be expected to apply fairly well to 500 mb charts and experience confirms that it is a useful indicator, but it needs to be emphasized that the situation is not a steady state, for the opposing divergences above and below the level require vertical motion and dynamical cooling or heating. It is readily seen that a wave form which is stationary, as regards the vertical integral of relative thermal divergence, has subsidence in the regions which, ignoring the variation in Coriolis parameter, would otherwise be anticyclonic, (A in Fig. 19) and ascent at the "cyclonic" inflexions (C in Fig. 19). The situation is still developmental in a general sense and the dynamical thermal changes will produce some change in the pattern and effects on weather.

In considering surface cyclogenesis or anticyclogenesis in sinusoidal patterns it is however desirable to consider in the first place the stationary mean wave length. Only the waves which are shorter than this are developmental and self-maintaining according to the mechanism described in 6 (c) above. Longer waves actually tend to anticyclonic building in the regions previously diagnosed as cyclonic (and *vice versa*); such situations are evidently not self-generating as the advective circulation due to the surface pressure features would tend to smooth out the distortion in the thermal field. It appears then that waves longer than the stationary value are self-destroying, in other words stable, and will not develop; big amplitude oscillations demand a shorter wave length.

There are however many complications. Variations in vorticity due to shear are often as important as variations due to curvature; the wave patterns are never

more than notionally sinusoidal and, moreover, may be oriented in directions departing widely from the latitudinal. The subject is a wide one to which we hope to return on another occasion.

7. Remarks on practical forecasting

The contribution to the principles of forecasting presented above is, in common with all earlier contributions, far from providing a scientific solution to the general problem. All that can be claimed is that a basis for a forecasting system has been indicated and this must be handed over to the profession of forecasting to adapt and modify in the light of experienced judgment — while research continues to explore the physical processes and to attempt more quantitative formulations. Nothing short of a professional text-book could begin to show how best to deal with the wide diversity of situations which arise in nature and how best to make allowances for topographical and seasonal controls according to the situation.

It may however be worth while to indicate briefly the procedure which some little experience has shown to be acceptable to forecasters. The problem as it was formulated is to construct forecast charts of thickness and pressure patterns from the sequence of charts of like kind. In principle there is only one, a three-dimensional, forecast and in practice expediency dictates procedure, but the following stages might in principle be preferred for the preparation of 24-hour forecast charts.

(a) *The analysis*

It would be worthless to attempt to say anything in a few words on the subject of chart analysis except to stress that observational data for one time are never sufficient to provide the best analysis. The patterns must evolve and forecasting principles enter into the analysis.

(b) *The physical interpretation*

This stage, a most important one, is often given scant attention. We are prepared to use physical arguments to forecast the future ; let us prepare always by using physical arguments to explain the recent past. If the situation is behaving well we may proceed with some confidence whereas, if our physical explanation is unsatisfactory, we must be more cautious — and problems for research are formulated. This attitude of mind is just as important for thermal patterns as for anything else. Unexpected warming or cooling must be explained somehow and not be dismissed as a peculiar phenomenon.

(c) *The preliminary prebaratic*

Over a period of 24 hours extrapolations of trends provide a most valuable first approximation but in using this method it is important to judge whether the processes, interpreted as dynamical steering or development in relation with the thickness pattern or as topographical peculiarities, have been changing their effect in the recent past or are likely to change in the forecast period. In this connexion stage (d) must be partly anticipated.

(d) *The pre-thickness pattern*

The forecast thickness pattern must be fitted to the prebaratic but the first step is to consider the thickness lines as material lines embedded in the low-level geostrophic wind and to estimate the amount of displacement at least at a number of salient points. This displacement will lead to a pattern which is markedly "overdrawn" but it will throw into prominence the regions of marked cold air and warm air advection and, what is quite as important, the regions of advective tightening (frontogenesis) or slackening (frontolysis) of the thermal gradients. Only very exceptionally does advection, on this basis, under-estimate the speed of displacement of a thickness line, the exceptions arising when cold air is moving from sea to land in winter or when warm air is moving with subsidence. In almost all other cases advective displacements must be relaxed although the amount of relaxation varies very much. The processes to allow for are dynamical warming or cooling in descent or ascent and the non-adiabatic processes — the surface heating of cold air and the radiative cooling of warm air. Research is in hand to give more quantitative guidance but experience quickly provides useful skill. It is also of great importance to check the adjusted patterns, drawn after making these allowances, with the climatological means and extremes and to ensure that exceptional displacements have not been unwittingly introduced without exceptional causes — remarkably strong advection or remarkably persistent subsidence. A further check is that of extrapolation of ridge and trough lines. It is undesirable to make the extrapolations first as the aim is to forecast variations from simple trends but it is necessary to check that the arguments which have resulted in peculiar displacements are sound according to the rules.

(e) *The general survey*

The combined forecast should finally be checked over for internal inconsistencies, especially to ensure that the pre-thickness chart has not introduced development features for which no allowance was made in the prebaratic. In practice mutual adjustment may be almost impossible in the time available but it should be attempted. Finally in surveying the finished product general professional judgment may suggest some redrawing to bring the patterns into harmony with experience ; where most processes have only been "estimated" there is usually some latitude for over-all adjustment but when the argument has been close and careful it must not give way to "flair" if progress is to be made. If the final solution is dynamically acceptable according to our development and steering principles, if the thermal changes satisfy what we know of the thermodynamical controls and if the whole is tolerable according to definite climatolological tests we have a sound solution which is a fair basis not only for a forecast but also for later study, for the classification of errors and for further research.

The continuation of the forecast for further periods of 24 hours up to several days may be carried out step by step although the emphasis changes. In the first place the area to be studied must be enlarged and all authorities are agreed that little less than a hemispherical basis is adequate. The extrapolation of evident

trends which carries the forecast through with much success for the shorter period becomes relatively unreliable and much more weight must be assigned to the physical argument. Indeed, when the situation after 24 hours is represented only by forecast isopleths, with no actual observations and no " tendencies," the familiar aids evaporate and physical arguments must fill their place. At the same time new problems concerning the large-scale circulation are thrown into prominence and long-wave conceptions, interactions between remote systems, type changes and blocking mechanisms become important. Much has been written on these topics in recent years, particularly in America, and it is hoped to take an early opportunity of presenting the conclusions which have been reached, using our thickness technique and the basic principles introduced in this paper, from experience at Dunstable. It may however be stressed here that a solution for several days ahead cannot be jumped at by mysterious arguments about processes unexplained, the situation must be shown to evolve without violating the known controls and the step-by-step process is a necessary discipline. Experience strongly suggests that the large-scale evolution is controlled by the same dynamical and thermal processes as control the smaller, more rapidly changing features and that the methods which we have developed can be powerful tools in the medium-range problem.

We say nothing here of the true long-range problem, that of foretelling the character of months or seasons ahead, except to remark that regular experience with the technique may throw out hints of importance. This problem is evidently that of the general circulation and some technique which throws the thermal field and its anomalies into prominence instead of hiding them in the flow pattern is clearly desirable. It is, for example, easy to obtain a measure of the amount of cold air in the polar basin or over the continents in winter, of the displacements of the belts of strong thermal gradient and of the abnormal preferred positions of cold and warm tongues which characterise an abnormal season ; these may not provide prognostic tools but they must be important indices.

8. Conclusions and further requirements

It is concluded that the representation of the atmosphere by an ordinary synoptic chart and the 1,000 — 500 mb thickness pattern (with the implied 500 mb contour pattern) is a valuable and practical simplification.

The forecasting problem in this simple form reduces to that of determining the evolution of the surface pressure field (including fronts) and the thickness patterns (implying also the 500 mb contour pattern).

A set of principles and rules, founded on dynamics, can be evolved which give considerable guidance in estimating the evolution of the surface field. These depend on the thickness pattern and the surface pattern and especially on the vorticity variations of the gradient and thermal winds.

A further set of principles, founded on dynamics and thermodynamics, can be evolved which give considerable guidance in estimating the evolution of the thickness pattern. Where theory is inadequate empirical climatology may help considerably.

Together, the principles, modified by experience, provide a basis for forecasting the situation step by step and estimating the evolution for a considerable period ahead.

All experience with this as with other techniques shows a steady falling off in forecasting accuracy to become of dubious value after a few days. It remains to be decided by further research whether this position can be improved

(a) by more complicated analysis and representation to take account of initial conditions more thoroughly.

Or (b) by giving more quantitative precision to the principles which are already used.

Or (c) by developing new principles taking account in some way of processes so far virtually ignored (in particular friction and radiation).

It is believed that the greatest need is for the physical research underlying (b) and (c) and that highly elaborate techniques to represent the complex behaviour of the atmosphere bring more confusion than profit to routine forecasting when the physical principles are not formulated with any corresponding precision.

Acknowledgment

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Charney, J. G.	1947	*J. Met.*, Lancaster, Pa., **4**, p. 135.
	1948	*Geofys. Publ.*, Oslo, **17**, No. 2.
Charney, J. G. and Eliassen, A.	1949	*Tellus*, Stockholm, **1**, No. 2, p. 38.
Petterssen, S., Sheppard, P. A., Priestley, C. H. B. and Johannessen, K. R.	1947	*Quart. J. R. Met. Soc.*, London, **73**, p. 43.
Rossby, C.-G.	1939	*J. Mar. Res.*, Newhaven, Conn., **2**, p. 38.
	1940	*Quart. J. R. Met. Soc.*, London, **66**, Supplement, p. 68.
Sawyer, J. S.	1950	*Met. Mag.*, London, **79**, p. 1.
Scherhag, R.	1948	*Wetteranalyse und Wetterprognose*, Berlin (Springer-Verlag).
Sutcliffe, R. C.	1939	*Quart. J. R. Met. Soc.*, London, **65**, p. 519.
	1947	*Ibid.*, **73**, p. 370.
	1948	*Met. Mag.*, London, **77**, p. 145.
Sutcliffe, R. C. and Godart, O. H.	1942	*Isobaric Analysis*, Met. Off., London, S.D.T.M. No. 50.

Notice of new publications

We are glad to take notice of three new journals which have reached the Society's office. The first is a monthly publication of the American Meteorological Society, entitled *Meteorological Abstracts and Bibliography*, of which Malcolm Rigby is Editor, and Vol. 1, No. 1 (pp. 78) is dated January 1950. The publication (price $3.00 per year) is to be devoted to :

(a) Current abstracts in English on important meteorological literature in every language ;

(b) Bibliographic references to other items of interest to the profession ; and

(c) Cumulative, annotated bibliographies on subjects of immediate and special interest to meteorologists.

As an example of what is intended under the last item, the number now to hand contains a 23-page bibliography on *Atmospheric Pollution*, covering the period 1661 — 1949. There is a preface indicating the development and scope of the undertaking (it had its origins in the classified bibliographies which have appeared fairly regularly in the *Bulletin* of the American Meteorological Society) ; a section on the methods of selection, construction and classification ; and a review of the nature and scope of thirty current meteorological and geophysical periodicals — our own *Quarterly Journal* and *Weather* receive very honourable mention here. The bibliography of papers occupies 26 pages arranged by subject, there is a list of papers and articles which have appeared in recently issued journals, under the titles of the latter, and a complete index of authors and subjects.

We extend a very hearty welcome to this publication of our sister society, for they are performing a most valuable service to meteorology and meteorologists the world over in this, their great undertaking. We congratulate the editor on the high standard which he has achieved in his first number and we shall look forward to the appearance of future numbers to provide the practising meteorologist with an aid which, we are sure, will become indispensable as the numbers grow.

The second journal to be noticed is named *Geophysics* and emanates from Tohoku University, Japan, under the joint editorship of Professors Nakamura, Kato and Yamamoto. Vol. 1, No. 1 (pp. 52) is dated February 1949, the contents being referred to as " The Science Reports of the Tohoku University, 5th Series " ; there is no mention of the proposed frequency of publication. The first issue contains five papers on meteorology and five on other geophysical subjects. From the former it is apparent that substantial work in meteorology is being undertaken in Tohoku — a paper on the absorption coefficient of water vapour in the infra-red region is clear evidence of this — and serious meteorologists would, we feel sure, be wise to inspect its pages. All the papers are in English.

We return to our own shores for the third new publication, the *British Journal of Applied Physics*, to be published monthly (price 6s.) by the Institute of Physics (of which ours is a Participating Society). Vol. 1, No. 1 (pp. 32) appeared in January 1950. The new journal is a development from the Institute's earlier practice of providing a part of the space of its now long-standing *Journal of Scientific Instruments* for papers on applied physics. The primary object of the new journal is to announce new applications of physics and developments of those already known, and, from the contents of the first number which range from internal friction in solids to multiple factor analysis, it is evident that its scope will be wide. There is no paper of particular meteorological interest in the first number but, with the present quite rapid growth in applied meteorology, we may expect to find this branch of applied physics being dealt with from time to time. Perhaps of more importance to meteorologists is that here is a journal in which they may expect to find new techniques described which may be turned to meteorological purposes. We wish it a successful and useful life.

EDITOR

Reviews

Crystal Growth. By THE FARADAY SOCIETY. London (Gurney and Jackson), 1949. Pp. 336 plus numerous plates. 30s.

The proceedings of a general discussion on Crystal Growth held under the auspices of the Faraday Society at Bristol in April 1949 have been published in book form. This volume contains some fifty papers covering a wide field and includes a number by foreign contributors. Many of them contain new and provocative ideas which stimulated a good deal of profitable discussion. The discussions are printed in full and they indicate that the present state of the subject allows for a good deal of speculation and difference of opinion in interpreting experimental results and observations.

The papers are divided into four sections :

(1) Theory of crystal growth ;
(2) Nucleation and normal growth ;
(3) Abnormal and modified crystal growth ;
(4) Mineral synthesis and technical aspects.

Of these, the first two are of considerable interest to the meteorologist concerned with the formation and growth of ice crystals. Although the main emphasis is on growth of crystals from solutions, and ice is scarcely mentioned in the whole book, much of the general theory of crystal growth from the vapour and liquid phases will be relevant to a study of ice crystal formation. The reviewer regrets that dendritic growth and growth of crystals from the melt did not figure more prominently in the discussions.

The theoretical studies of Frank, Burton and Cabrera on the rate of growth of crystals from the vapour and its relation to surface structure are of particular interest and importance. The classical theory of growth by two-dimensional nucleation on perfect crystal surfaces, as developed by Volmer, Becker and Döring, and Stranski, predicts growth rates which are vanishingly small at normal supersaturations, whereas observable growth occurs in the case of iodine at supersaturations of less than 1 per cent. Burton and Cabrera show that the Volmer result is not appreciably modified even when surface diffusion of the molecules is taken into account, and conclude that growth can occur only on stepped surfaces. They proceed to derive an expression for its rate of growth as a function of the surface density of steps and the supersaturation.

In view of the importance of their work it is a pity that it should be presented in such a condensed form with a minimum of discussion on the physical processes involved. It is to be hoped that a complete treatment will appear elsewhere. Perhaps two errors which appear in their equations should be pointed out. Eq. (4) of Part II of their paper should read :

$$j = \frac{2\nu}{a} e^{-W/KT} \frac{1}{\beta} \tan h\, \beta\, x_0\, (\alpha - 1)$$

and Eq. (21) :

$$\alpha - 1 \sim 2\sqrt{2\pi}\, \frac{\gamma}{KT}\, N^{\frac{1}{2}}\, a\ .$$

Frank, in a very interesting paper, suggests that steps normally appear in a crystal face by termination of ' screw ' dislocations in the surface, and that growth can occur at the edges of these steps without the need for two-dimensional nucleation. The presence of these dislocations was first invoked to explain the fact that the mechanical strength of a metal crystal is much less than the theoretical strength of a perfect crystal, a surface density of about 10^8 dislocation lines per cm^2 being required to explain the discrepancy.

Burton and Cabrera apply their theory of growth on stepped surfaces to a surface of an iodine crystal containing a similar density of dislocations and show that the growth rate as deduced theoretically agrees well with the value observed by Volmer and Schultze.

The material in this volume will not be easy to a reader quite new to the subject. Although each section is prefaced by a paper of an introductory character, this is essentially a collection of original contributions and no attempt is made to synthesize them — if indeed such synthesis is yet possible ! It serves rather to emphasise the gaps and the problems in this complex field which has by no means reached the text-book stage. That it records some important advances and some new and significant ideas cannot, however, be denied.

The papers on the whole are clearly and concisely written and many are illustrated with excellent plates.

B.J.M.

Theoretical Hydrodynamics. By L. M. Milne-Thomson. London (Macmillan and Co. Ltd.) 2nd edition, 1949. Pp. 600 + xxv ; 4 plates and figures in text. 60*s*.

This is the second edition, largely rewritten, of a book first published in 1938, based on lectures given at the Royal Naval College, Greenwich. Those who know Professor Milne-Thomson's mathematical work will expect both rigour and lucidity, and in this they will not be disappointed.

There is a natural tendency to regard fluid mechanics as a subject with two aspects : one, the largely abstract branch of mathematics represented by Lamb's *Hydrodynamics* and the other the physical science developed in Goldstein's *Modern Developments in Fluid Dynamics.* The present work leans much more to Lamb than to Goldstein, but differs essentially from the two standard works of reference in that it is essentially a book for students learning hydrodynamics for the first time, and it is as such that it should be judged. The greater part of the book is occupied with the development of the dynamics of a frictionless fluid by the methods of vector analysis and the complex variable. Treated in this way, hydrodynamics lends itself to exact analysis and elegance of presentation, and Professor Milne-Thomson is far too good a mathematician to miss any opportunities.

Most of the topics treated are those normally included in a course of classical hydrodynamics, such as sources and sinks, flow around bodies, jets, vortices and waves, but in addition there is a very good account of two-dimensional motion leading to the elements of aerofoil theory and the generation of wing profiles by conformal mapping. This part of the book could hardly be bettered. Viscous flow is treated more briefly, and one suspects that Professor Milne-Thomson has little sympathy with the less precise methods of present-day aerodynamics — boundary-layer theory is introduced but dismissed as " a useful guide to experimental work," whose applications have been so far " of a tentative and empirical character." It would be hard for the newcomer to the subject to realise, from these words, the extent of the revolution worked in fluid dynamics by Prandtl's physical insight. The final chapter on compressible flow, new to this edition, is a remarkably clear introduction to a subject which bristles with difficulties.

The main purpose of the book, as its title indicates, is the exposition of the theoretical basis of hydrodynamics, but even so, the student would get a better grasp of the subject if the physical aspects were more emphasized and especially if it were constantly made clear how far the theoretical solutions agree or disagree with the corresponding phenomena in a real fluid of low viscosity, such as air. It is also a little difficult to understand why, in a treatise on hydrodynamics, it is necessary to include extremely condensed accounts of vector analysis and of the theory of functions of a complex variable. The student meeting these subjects for the first time is likely to find these chapters exceedingly difficult because of this condensation, and it is better to face the fact that it is impossible to make headway in classical hydrodynamics without an adequate preliminary training in pure mathematics. Apart from this, Professor Milne-Thomson's book can be recommended to those who desire a clear and rigorous presentation of the dynamics of an inviscid fluid, but it is likely to be more useful to the student of aerodynamics than to the budding meteorologist.

A useful and attractive feature of the book is the large collection of examples (over 500) to be worked by the reader. The mathematical type-setting is excellent and the figures are clear and well drawn. Apart from a few minor blemishes (such as the appearance of the familiar " Q.E.D." of Euclid at the end of every proposition) the work is throughout of the high standard to be expected from the author and the publishers.

O.G.S.

Earthquakes and Mountains. (2nd Edition, revised). By Harold Jeffreys, M.A., Sc.D., F.R.S. London (Methuen and Co.) 1950. 8 vo. Pp. 191 ; 6 plates, 9 figures. 12*s*. 6*d*. net.

The first edition of this book appeared in 1935 and was reviewed at some length by the late Dr. F. J. W. Whipple in the *Quarterly Journal* for October of that year. Dr. Whipple concluded his review by predicting that the author would find it necessary in another edition to give his views on some subjects at greater length. In the revised edition recently published Professor Jeffreys has, in fact, done so for two of the subjects that he dealt with rather briefly in the first edition. He has included some remarks on modern ideas about the origin of the solar system and their implications with regard to a gaseous origin of the earth. He has also given a longer discussion of Wegener's theory of continental drift and its failure to fit in with geophysical evidence. In this connection Professor Jeffreys considers that much of the evidence from palaeoclimatology put forward in favour of continental drift shows strong signs of selection. He suggests that we have insufficient evidence as to why climates change and that what is needed is a comprehensive account of the facts relevant

to former climates and land connections, unbiased by any particular theory. In this section of the book the author has also added an interesting discussion of the newer theories of convection in the interior of the earth.

Apart from some minor revisions the rest of the book remains practically unchanged. It provides a very readable account of the physical development of the earth and most meteorologists should find a good deal in it to interest them.

F.J.S.

Rainfall Map of Great Britain, compiled by Ministry of Town and Country Planning. London 1949. Two sheets, 40″ x 32″. 5*s*. each sheet.

An important new rainfall map of this country, compiled by the Ministry of Town and Country Planning and the Department of Health for Scotland on the basis of data supplied by the Meteorological Office and published by the Ordnance Survey, on the large scale of ten miles to the inch is divided into a Northern and Southern sheet at five shillings each. Where the isohyets are crowded together in the mountainous areas of heavy rainfall they are drawn at ten-inch intervals, but elsewhere they are drawn at five-inch intervals except that in the drier eastern areas where there is little local variation in the mean values isohyets for 27·5 and 22·5 in. appear. Inset graphs are given for certain representative stations, based on the period 1881-1915, showing seasonal variation as well as liability to deviations from normal.

The close dependence of the mean annual rainfall of Britain upon the relief of the land is most impressively indicated by various shades of blue. Values range from upwards of 150 in. in the Western Highlands, the Lake District and Snowdonia to slightly downwards of 20 in. at the Thames Estuary, chiefly on the Essex side. Even such a minor hill range at the Lincolnshire Edge can easily be picked out. All the evidence provided by this detailed new compilation serves to confirm one's doubt whether, if Britain were a uniform plain, any part of the West would have a rainfall over 40 in. or any part of the East below 30 in. The actual extensive areas above 40 and below 30 are the result of orographic influences such that every place should be regarded as having either a plus or minus orographic component in its rainfall. Thus London's low rainfall of 25 inches would be due to a minus orographic, that is rain-shadow, effect.

L.C.W.B.

Corrigendum to Vol. **76.** Plate facing p. 98.

Transpose figures (*a*) and (*b*) and similarly figures (*e*) to (*f*).

Canadian Branch

The Annual Meeting of the Canadian Branch was held in Toronto on 19 January 1950, and the following members were elected to the Executive Committee for the year 1950 :

President	P. D. McTaggart-Cowan
Vice-President	H. W. Halbert
Secretary	F. W. Benum
Treasurer	M. K. Thomas

Councillors-at-Large

G. L. Pincock	Vancouver
Prof. F. K. Hare	Montreal
R. A. Hornstein	Halifax
H. Cameron	Winnipeg
C. E. Thompson	Edmonton

In addition to the above, Mr. Andrew Thomson was nominated to represent Canada as Vice-President of the Royal Meteorological Society.

Report of the Council

for the year 1949

(Submitted to the Annual General Meeting, 25 January 1950)

General

During the year under review the Society has come to the eve of its centenary in full vigour and with a numerical strength that would probably have surprised the most optimistic of the founders. Although the total membership has shown a slight decline from the peak figure of 1714 reached in 1947, it remains at substantially more than double the pre-war level in spite of the difficulties of the times and the increased subscription which became necessary three years ago. Full details of the gains and losses since 31 December 1948 are given below. The Council consider the state of the Society in this respect to be highly satisfactory.

Table A

	Fellows & Foreign Members			Associates	Student Associates	Honorary Members	Total
	Annual	Life	Total				
31 Dec. 1948	1,298	197	1,495	97	57	13	1,662
Since admitted	+101	+5	+106	+31	+9	—	+146
Re-admitted	+9	—	+9	+2	—	—	+11
Transferred	—	+1	+1	—	−1	—	—
Deceased	−9	−7	−16	—	—	—	−16
Resigned	−137	—	−137	−8	−4	—	−149
31 Dec. 1949	1,262	196	1,458	122	61	13	1,654

The inflow of scientific communications, both for the *Quarterly Journal* and for the magazine *Weather*, has been well maintained; 48 papers have been submitted for publication in the *Quarterly Journal* during 1949, against an annual average of 23 over the pre-war decade 1930-1939. It is a source of gratification to the Council that arrears of publication with the Society's chief organ have at last been virtually overtaken ; the issue of the *Quarterly Journal* for October 1949 was

distributed within a few days of the close of that month. The Council record their gratitude to the retiring Editor, Dr. R. C. Sutcliffe, to his assistants among the Fellows and on the office staff, and to the Lewes Press, through whose joint efforts the regretted delay resulting from wartime and post-war obstacles has been brought to an end.

During the summer a committee of the Council was appointed to advise on the mode of celebrating the Society's centenary, which falls on 3 April 1950. An attractive and comprehensive programme has been drawn up. As already announced elsewhere, this will include scientific symposia at Oxford, visits to the Meteorological Office, Harrow, and to the Department of Meteorology, Imperial College of Science and Technology, a conversazione and a centenary meeting at the Society's headquarters, and a centenary dinner in the Connaught Rooms. There will also be a meteorological exhibition at the Science Museum and a special B.B.C. feature programme concerned with the Society's history and activities during the hundred years 1850-1950. The Council are confident that the commemoration of the anniversary has been so arranged as to have its appeal to every Member, professional and amateur. Preparations are being made for complete rehabilitation and redecoration of the Society's premises before the centenary celebrations.

By arrangement with Mrs. Clarke the Council have acquired on behalf of the Society the entire collection of about 600 cloud photograph negatives taken by the late Mr. G. A. Clarke, F.R.P.S., of Aberdeen, together with a large number of prints. Enlargements from some of the best of these are being framed for display in the Society's rooms and the Science Museum at the time of the centenary.

Membership

As will be seen from the table A, total membership has changed little during the year, new admissions into the Society having fallen short of losses through deaths, resignations and other causes by eight. Most of the Members who have resigned are young men whose war-time duties brought them temporarily into contact with meteorology.

The Council record with regret the deaths of the following Fellows and other Members ; dates of election are appended to the names.

C. Anthony (Life Fellow, 1906)
G. A. Clarke (1919)
J. H. Coste (1935)
W. Dunbar (1928)
C. C. Easterbrook (Life Fellow, 1909)
R. Feige (Foreign Member 1946)
W. R. H. Masters (1944)
Dr. R. T. Moore (Life Fellow, 1919)
G. Nicolson (1922)
J. B. Phillips (1916)
Miss E. L. Ramsay (Life Fellow, 1906)
Rev. J. P. Rowland, S.J. (1933)
D. S. S. Steuart (Life Fellow, 1907)
R. R. Waite (1945)
J. R. Weeks (Foreign Member, 1933)
Prof. J. H. M. Wedderburn, F.R.S. (Life Fellow, 1908)
A. Wilson (Life Fellow, 1899)

Mr. William Dunbar, M.Inst.M. & Cy.E., who died on 19 December 1948 at the age of 59, was Burgh Surveyor of Kilmarnock for nearly a quarter of a century and served the Society with high efficiency as Scottish Secretary from 1937 to 1945. He held office as Vice-President in 1946 and 1947.

Mr. George Aubourne Clarke, F.R.P.S., whose death in his 70th year occurred on 13 February 1949, had a world-wide reputation as a cloud photographer and was twice awarded the Royal Photographic Society's medal for the best print shown at an exhibition. He was a member of the observatory staff at King's College, Aberdeen from 1903 to 1943.

Meetings

Dr. G. M. B. Dobson, F.R.S. delivered the Presidential Address after the Annual General Meeting on 26 January, his subject being "Ice in the atmosphere."

The ordinary meetings of the Society were as follows ; unless otherwise stated they were held in the Society's rooms :—

16 February. There was a discussion on " Large-scale vertical motion in the atmosphere " which was opened by J. K. Bannon, B.A., who based his contribution on his paper " The estimation of large-scale vertical currents from the rate of rainfall " (*Q.J.*, vol. 74, p. 57). Mr. R. C. Graham's paper " The estimation of vertical motion in the atmosphere " (*Q.J.*, vol. 73, p. 407) was also discussed.

16 March. A discussion was held on "Meteorology in agriculture," which was opened by Dr. H. L. Penman, Dr. L. Broadbent and R. W. Gloyne, B.Sc.

20 April. Dr. G. E. R. Deacon, F.R.S. delivered the Symons Memorial Lecture, and his subject was "Waves and swell."

18 May. A discussion was held on " The general circulation of the atmosphere." It was opened by Dr. E. T. Eady, and a recent paper by C. H. B. Priestley, M.A., entitled " Heat transport and zonal stress between the latitudes " was read. Dr. R. C. Sutcliffe also contributed to the discussion.

15 June. The following papers were read. " The dissipation of scattered and broken cloud " by E. W. Hewson, M.A., Ph.D., F.R.S.C. (*Q.J.*, vol. 74, p. 243) ; and " Synoptic applications of the frontal contour chart : the motion of selected lows, 5-7 November 1946 " by A. M. Crocker, M.A. (*Q.J.*, vol. 75, p. 57).

16 November. The following papers were read :— By F. Pasquill, B.Sc., " A portable indicating apparatus for the study of temperature and humidity near the ground " ; " Some estimates of the amount and diurnal variation of evaporation from a clayland pasture in fair spring weather " (*Q.J.*, vol. 75, pp. 239 and 249). By C. S. Durst, B.A. and G.H. Gilbert, B.Sc., " Constant height balloons – calculation of geostrophic departures (*Q.J.*, in course of publication).

21 December. The following papers were read :— By F. H. Ludlam, " The composition of coagulation-elements in cumulonimbus " (*Q.J.*, in course of publication). By M. K. Miles, M.Sc. " Air motion ahead of warm fronts " (*Q.J.*, vol. 75, p. 389).

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13 July. The Society visited the Royal Aircraft Establishment at Farnborough. After a welcome and address by the Director, Mr. Perring, the party of 76 saw a demonstration of the pilot-ejection rig and spent the rest of the morning in the Structures Laboratory and the Metallurgy Department. In the afternoon the Meteorological Research Flight and the Flying Control Tower were visited.

23 November. A Joint meeting with the London Branch of the Institute of Physics was held at the Royal Institution of Great Britain, 21 Albemarle Street, W.1., when a paper on " Physics of atmospheric pollution " was read by Dr. A. R. Meetham and followed by a discussion.

In addition to the ordinary meetings of the Society, a series of Popular Lectures was held in the Lecture Theatre of the Science Museum as follows :—

12 January. Sir George Simpson, K.C.B., C.B.E., D.Sc., F.R.S., delivered a lecture entitled " Atmospheric electricity during the last 50 years."

10 February. Sir Nelson K. Johnson, K.C.B., D.Sc., delivered a lecture entitled " Some international aspects of meteorology."

3 March. Professor G. Manley, M.A., M.Sc., delivered a lecture on " British climatic fluctuations since Queen Elizabeth's day."

6 April. Dr. G. M. B. Dobson, F.R.S., delivered a lecture on " Some solar and terrestrial relationships."

5 May. Mr. E. Gold, C.B., D.S.O., F.R.S., delivered a lecture entitled " Meteorology in the First World War."

Meetings of provincial centres

Midland Centre

25 January. A meeting was held at which Dr. J. Glasspoole spoke on " The development of our knowledge of rainfall over the British Isles during the last 30 years."

The second Annual Summer Outing was held on 21 May, when a party visited Kew Observatory by coach.

25 October. Captain L. G. Garbett, C.B.E., R.N., spoke on "The history of the Beaufort Scales " at Birmingham University.

Scottish Centre

Meetings were held at Edinburgh University unless otherwise stated.

18 February. Meteorological films were shown.

11 March. W. G. Gray, M.A., B.Sc., read a paper on " Meteorological factors determining the development of plant pests and diseases."

9 June. A meeting was addressed by Sir Nelson Johnson, who spoke on the organisation of the Meteorological Office.

1 November. Professor G. Manley spoke on "Climatic aspects of the glaciation of Scotland."

16 December. A general meeting was held to elect office-bearers. F. P. Henderson then gave a lecture on " Greenland Expeditions."

Canadian Branch

The Annual Meeting of the Canadian Branch was held on 14 January in Toronto.

24 February. Mr. George Jacobson gave a talk on the difficulties of house building in the Arctic.

31 March. Mr. MacTaggart-Cowan gave a report on the Annual General Meeting of the American Meteorological Society which took place in New York in January.

28 April. Mrs. Marie Sanderson spoke on " Potential evapotranspiration and the climate of Canada."

26 May. Brigadier General D. N. Yates, addressed the meeting on" Meteorological service for the Berlin Air-Lift."

Awards

The 24th award of the *Symons Memorial Medal* was made to Dr. Tor Bergeron, Professor of Meteorology in the University of Upsala, for his distinguished meteorological work, relating in particular to air mass analysis, the technique of weather forecasting and the physics of precipitation. In the absence of the Medallist the presentation was received on his behalf from the President by the Swedish Chargé d'Affaires at the Annual General Meeting on 26 January 1949.

Darton Prizes 1948. On the same occasion the first of these was awarded to Mr. F. H. Ludlam for a valuable digest of recent research on the physics of condensation nuclei and cloud particles ; the second prize went to Mr. C. A. Wood for an analysis of meteorological observations made in the Borneo-Celebes region. Dr. J. E. Belasco was accorded honourable mention for his statistical studies of synoptic climatology published by the Society.

Sir Napier Shaw Competition 1948. The following awards were announced in May 1949 :— Senior Section, first prize withheld ; second prize to F. W. M. Ruck ; Junior Section, first prize to R. M. Glaister ; second and third prizes withheld. The adjudicators considered the entries disappointing in both quality and number.

Publications

As already indicated, delay with the production of the *Quarterly Journal* has been progressively reduced during the year under review from several months to a few days, the issue for January 1949 having appeared late in April and the issue for October 1949 early in November. The four numbers together contain 447 pages, an increase of 19 on the 1948 volume and a close approximation to the average maintained in the years immediately preceding the War.

" Weather," the monthly magazine founded by the Society in May 1946, has continued to thrive and to gain popularity. There were several changes in the editorship during 1949, Dr. J. S. Forrest and Wing Comdr. R. M. Poulter, two of the original editors, having been succeeded by Mr. C. D. Ovey, Mr. J. S. Sawyer and Instr. Comdr. F. L. Westwater, who, together with Mr. O. M. Ashford and Dr. A. R. Meetham, now guide the destinies of the magazine. Mr. T. H. Kirk also acted in editorial capacity from March to July. The Council wish to record their high appreciation of the able services rendered to the Society by all these Fellows, as well as by Dr. R. C. Sutcliffe, whose term of office as editor of the *Quarterly Journal* ends in January 1950. Special tribute is due to Mr. Ashford for his success in extending the appeal of " Weather " as an advertisement medium.

In April 1949 a printed List of Members was distributed by the Society for the first time since 1939. Mainly for reasons of economy it has been decided to discontinue the *Bibliography of Meteorological Literature*. This publication, prepared jointly by the Society and the Meteorological Office, has served an important purpose for more than a quarter of a century ; but the Council believe that its place will henceforward be sufficiently filled by other serial bibliographies issued in England and abroad ; this view is shared by Sir Nelson K. Johnson, Director of the Meteorological Office, whose opinion was sought before the decision for discontinuance was taken.

The new edition of the late Richard Inwards's book *Weather Lore*, which had been in preparation by Mr. E. L. Hawke at the request of the 1947 Council, was sent to Press in October and is to be published for the Society during the spring of 1950 by Messrs. Rider & Co., an associate firm of Hutchinsons, Ltd.

Staff

The year has seen an almost complete reconstitution of the Society's administrative and clerical staff. The resignation of Mrs. W. H. Hayman from assistant secretaryship, announced in the Report of the Council for 1948, took effect at the

close of January 1949. Commander C. R. Burgess, O.B.E., R.N., Executive Secretary since April 1947, resigned to take up an appointment as Secretary of the Marine Society in August 1949. The Council report with satisfaction that the services of Commander Burgess have nevertheless not been wholly lost to the Society : he continues to give valued help with the sub-editing of the *Quarterly Journal* and on the Editing Committee, and also contributes a page on the meteorological characteristics of each month to the magazine *Weather*. Since August the post of Assistant Secretary has been very competently filled by Mr. M. E. Shoenberg, B.A., who has brought wide business experience as well as scientific and mathematical training to bear on his duties. Mrs. J. A. C. Cook, efficient clerk for the magazine *Weather*, is the only staff member who has served the Society throughout the year.

Among the clerical staff, Mrs. W. M. Adams, Mrs H. M. Hunwick, Miss D. F. Hyams, Mrs. D. Musson and Miss J. Smith all worked well in various capacities during 1949, but responded to other calls on their time and energies before 31 December. At the close of the year the clerical staff acting under Mr. Shoenberg's direction consisted of Miss E. O. Faber (accountant, appointed in February), Miss I. Dickinson (library assistant, appointed 22 September), Mr. R. H. Mason (junior clerk, appointed 28 September), and Miss M. Kline (secretarial assistant, appointed 1 November). All have performed their duties to the Council's satisfaction.

Canadian Branch

From draft reports submitted by Mr. F. W. Benum, the Secretary, it is evident that the Canadian Branch continues in high and increasing activity. At a meeting of the executive held in Toronto on 27 October 1949 approval was given to a suggestion that the Branch should participate in the centenary celebrations of the parent society by sending at least one representative and by sponsoring an exhibition in London of Canadian meteorological instruments, climatological maps, and photographs.

British Rainfall Organization Fund

With 1949 was completed the 93rd consecutive year of regular records at the historic meteorological station (formerly headquarters of the British Rainfall Organization) in Camden Square, London, N.W., which has been the responsibility of the Society since 1923. Mr. and Mrs. A. H. Dodd have again acted efficiently as resident observers. As usual, the observations have been supplied by telephone to the Meteorological Office each morning for inclusion in the *Daily Weather Report* and full written returns have been prepared for the *Monthly Weather Report*. Mr. A. J. Drummond, who had for some years devoted a substantial amount of time to supervising the work at the station, was appointed to an oversea post in September

1949 and thus can no longer undertake this duty on the Society's behalf. The Council wish to express their appreciation of his valuable services.

It has recently been decided to draw on the British Rainfall Organization Fund for the institution of a new award, to be known as the Hugh Robert Mill Medal and Prize, in honour of the distinguished geographer who succeeded Mr. G. J. Symons and Mr. Sowerby Wallis as head of the Organization and who was President of the Society in 1907-08. This award is to be made for work of outstanding merit in relation to rainfall. A design for the medal has been approved, and preparation of the dies was put in hand by Messrs. Pinches during the autumn.

Phenological work

The Council's hope, expressed last year, that some organization possessing suitable biological qualifications would come forward to take over from the Society responsibility for the 75-year-old annual phenological survey of Great Britain has not yet been fulfilled. Inquiries, one or two of them not without promise, are still being made to this end. It has therefore been decided that to prevent any break in the unique series of records all phenological observers shall be invited to continue their work during 1950 and supply their data to the Society on the usual forms, as hitherto. The Council are greatly indebted to Mr. R. A. Tyssen-Gee, who has kindly undertaken the heavy task of collating and tabulating the returns received since the retirement of Major H. C. Gunton M.B.E., Phenological Director to the Society from 1937 to 1948.

Library

Endeavours to fill the post of Honorary Librarian to the Society, left vacant by the resignation of Dr. C. E. P. Brooks, have not yet met with success. It is regretted that partly for this reason and partly because of very heavy calls made by other urgent duties on the time of the constantly changing office staff the work of re-organising the Library and revising the catalogue has progressed only slowly during 1949. To provide space for important modern publications a number of shelves and cupboards have been cleared of old books and magazines now regarded as having little or no scientific value, and arrangements are in hand for a large body of manuscript observational material possessed by the Society to be transferred to the library of the Meteorological Office at Harrow, where it will supplement the national sources of information. A bound set of *Nature*, 1874-1947, has been sold for the sum of £100 to the Bureau of Mineral Resources, Canberra. Although Dr. Brooks's valued services as Honorary Librarian have not been available during 1949, he has continued to give the Society the benefit of his long experience in library affairs. The Council desire to record their appreciation of his advice and willing attendance to requests.

Books

Among the books added to the Library during the year are :—

J. Alan Chalmers, *Atmospheric Electricity.*
Frank W. Lane, *The Elements Rage* (revised edition).
H. W: son Ahlmann, *Glaciological Research on the North Atlantic Coasts.*
J. G. Porter, *The Night Sky.*
Arthur J. Starr, *A First Book of Meteorology.*
H. Wichmann, *Physikalische Forschung, Herausgegeben von Pascual Jordan, Heft I. Grundprobleme der Physik des Gewitters.*
Cheng Cwen-Shu, *Chinese Synoptic Weather Patterns.*
G. Grimminger, *Analysis of temperature, pressure and density of the atmosphere extending to extreme altitudes.*
J. A. Fleming, *Terrestrial Magnetism and Electricity.*
Richard Scherhag, *Neue Methode der Wetteranalyse und Wetterprognose.*
A. E. Herbert Meyer and E. O. Spitz, *Ultraviolette Strahlen.*
Alfred Philippson, *Das Klima Griechenlands.*
W. G. Kendrew, *Climatology Treated Mainly in Relation to Distribution in Time and Place.*
O. G. Sutton, *Atmospheric Turbulence.*
Meteorologisches Amt für Nordwestdeutschland, *Klimatologie des Mittelatlantischen Ozeans.*
David Shoenberg, *Magnetism.*
Hellmut Berg, *Allgemeine Meteorologie.*
L. S. Berg, *Otkrytiye Kamchatki i Ekspeditsii Beringa.* (The Discovery of Kamchatka and Bering's Expeditions)
L. S. Berg, *Ocherki po Istorii Russkikh Geograficheskikh Otkrytiy.* (Studies in the History of Russian Geographical Discoveries)

Maisonette

There has again been no change in the tenancies of the three flats on the upper floors of the Society's house in Cromwell Road.

Finance

As was foreseen, 1949 has been a difficult year financially. The income from annual subscriptions which in the two previous years – that is, from the date of the increased subscription rate – averaged a little over £4,000, has fallen to some £3,800, which sum includes a disappointingly small proportion of the large number of subscriptions in arrear and outstanding on 1 January (to which reference was made in the last Report). At the same time it has not been found possible to make any effective reduction in the cost of administering the Society's affairs. The cost, indeed, still tends to rise with the general fall in the purchasing value of money.

Two special items of expenditure may be noted: the purchase at a cost of £200 of the late Mr. G. A. Clarke's famous and unique collection of about 600 negatives of cloud photographs, together with many fine prints ; and the purchase at a cost of £100 of an "Addressograph" outfit. The latter has already proved a most valuable time-saver and fully justifies the initial expense.

During the year the final stage was reached in overtaking arrears of publication which accumulated during and immediately after the war ; this entailed the realisation of the major portion of the securities held in reserve to that end. Fortunately the transactions were carried through before the recent serious fall in the value of Stocks.

The Council gratefully acknowledge the help given by the Royal Society Committee in allocating the sum of £500 to the Royal Meteorological Society from the Government Publications Grant Fund, together with an additional sum of £100 for library expenditure.

While keeping the accounts of *Weather* wholly separate from the Society's general account, the Council decided that the finances of the magazine should be assimilated with those of the Society as from 1 January 1949. At the same time large economies in production were planned, and increased income from advertisements was anticipated. The effect has been to reduce the cost of providing the magazine gratis to Members of the Society by a very substantial amount as compared with 1948, and the Council have therefore deferred for future consideration the proposal, mentioned in last year's Report, to ask Members to pay a small sum for their copies, although such a charge might be expected to provide a welcome addition to the income of the Society.

Napier Shaw Memorial Fund. This fund has been in a nearly stationary condition during the year and remains far below the amount which it was hoped to raise. In March 1949 £370 was invested in the purchase of £350 3½% Conversion Loan.

Lectures

In response to requests, Wing Comdr. R. M. Poulter addressed the Tunbridge Wells Natural History and Philosophical Society on 21 January, taking as his subject "Weather Forecasting," and Comdr. C. R. Burgess gave lectures to the Rotary Clubs of Wimbledon and Bermondsey on 14 September and 10 October respectively, each dealing with the work of the Royal Meteorological Society and modern methods of weather prediction.

Instruments

With one exception all the meteorological instruments on loan from the Society are reported to be in good condition and satisfactorily serving their purpose. The maximum thermometer in use at the Widecombe-in-the-Moor climatological

station was accidentally broken by the deputy observer during the summer; to avoid loss of record, prompt replacement was courteously made by the Meteorological Office.

Donations

The Council record their gratitude to Mr. C. J. P. Cave, M.A., J.P., F.S.A., a Fellow of 50 years' standing and a former President of the Society, for the gift of twelve enlarged and mounted prints from the well-known cloud photographs taken by himself, and for the presentation of documents and charts from autographic instruments relating to the ice-storm of January 1940.

Representatives

The following is a list of the Society's representatives on other scientific bodies :—

Geophysical Committee of the Royal Astronomical Society.
Professor S. Chapman, appointed 1939.

National Committee for Geodesy and Geophysics.
Professor S. Chapman, appointed 1946 ; Mr. E. Gold, appointed 1949.

Board of the Institute of Physics.
Dr. J. S. Forrest, appointed 1948 (until 30 Sept. 1949).
Dr. G. D. Robinson (from 1 Oct. 1949).

British National Committee for Physics.
Dr. F. J. Scrase, appointed 1948.

Research Committee, British Gliding Association.
Dr. A. E. Slater, appointed 1946.

The Meteorological Committee of the University of Cambridge.
Assistant Professor P. A. Sheppard.

Advisory Committee for the Meteorological Office, Edinburgh.
Mr. J. Paton was appointed in March 1949 to serve as the Society's representative in place of the late Mr. W. Dunbar.

STATEMENT OF RECEIPTS AND PAYMENTS

RECEIPTS

	£ s. d.	£ s. d.
Balance from 1948. Cash at Westminster Bank Ltd.		181 7 7
Subscriptions for 1949	3443 10 8	
,, ,, former years	297 17 10	
,, ,, 1950	166 1 4	
		3907 9 10
Entrance Fees		109 4 0
Dividends and Interest		93 13 2
Sale of Publications, advertisements, etc.		1128 4 4
Royalties from Clarke Cloud Photographs		5 18 6
Contribution for administrative purposes from the British Rainfall Organization Fund		15 0 0
Grant made by the Royal Society from Government Publications grant		500 0 0
Amount transferred from Life Composition Fund		197 0 0
Amount transferred from Staff Pension Fund		130 0 0
Rent of Maisonette		305 16 0
Sale of *Nature*		100 0 0
Sale of £900 2½% Consols		724 0 9
		£7397 14 2

17 *January* 1950

FOR THE YEAR ENDING 31 DECEMBER 1949

PAYMENTS

	£ s. d.	£ s. d.
Publications, etc.—		
Quarterly Journal, five numbers, July 1948 to July 1949 inclusive	1901 2 11	
Illustrations	165 12 5	
Reprints of Papers	158 11 8	
Reviews	20 15 3	
Advance to *Weather* on account of members' copies	300 0 0	
Bibliography of Meteorological Literature—Vol. VI, 1-4	342 3 0	
Second-hand Journals	54 7 10	
		2942 13 1
Printing—		
General Printing	263 3 5	
Stationery	198 17 2	
Books and Binding	64 15 6	
		526 16 1
Office Expenses—		
Salaries, Pensions and Insurance	2051 10 5	
Cleaners and Insurances	224 15 9	
Furniture and minor repairs	144 12 7	
Auditing Accounts for 1948	21 0 0	
Telephone Charges	35 9 10	
Petty Expenses	133 17 7	
Postage	374 18 9	
		2986 4 11
Coals, Lighting, Insurance, etc.—		
Coal and Coke	34 8 10	
Lighting and Gas	52 4 2	
Water Rate	10 0 0	
Insurance	11 10 0	
		108 3 0
Meetings—		
Expenses and refreshments at meetings	38 16 0	
Scottish Centre meeting expenses	15 0 0	
Midland Centre meeting expenses	16 12 0	
		70 8 0
Maisonette—		
General Rate to 31.3.50	106 5 0	
Water Rate to 31.3.50	12 10 0	
Repairs	19 19 3	
		138 14 3
Miscellaneous Expenditure—		
Rebate of subscriptions to Canadian Branch	84 6 9	
Rebate of entrance fees to Canadian Branch	10 6	
Purchase of Clarke Collection of Cloud Photographs	200 0 0	
		284 17 3
Payments on behalf of *Weather*		251 11 6
Centenary Expenses		14 8 2
Transferred to Pension Fund		50 0 0
Cash at Bank—		
Westminster Bank and in hand	16 7 11	
Post Office Savings Bank	7 10 0	
		23 17 11
		£7397 14 2

Examined, compared with vouchers, and found correct.
BALL, BAKER & CO.,
Chartered Accountants

SPENCER HOUSE, SOUTH PLACE,
LONDON, E.C.2

ASSETS AND LIABILITIES,

LIABILITIES

	£ s. d.	£ s. d.
Subscriptions paid in advance	166 1 4	
Subscriptions to publications paid in advance	81 11 10	
		247 13 2
Accounts outstanding—		
Quarterly Journal and reprints, October 1949	507 6 1	
Bibliography	110 0 0	
Sundry expenses	28 2 3	
		645 8 4
Excess of Assets over Liabilities		7796 18 7
This excess is exclusive of the value of the Library and the Stock of Publications.		
		£8690 0 1

17 *January* 1950

LIFE COMPOSITION FEES FUND,

RECEIPTS

	£ s. d.	£ s. d.
Balance from 1948 — Cash at Westminster Bank	87 15 10	
Cash on deposit in Post Office Savings Bank ..	63 14 6	
		151 10 4
Composition fees received during 1949		270 0 0
Interest on investments		86 16 1
		£508 6 5

17 *January* 1950

31 DECEMBER 1949

ASSETS

	£ s. d.	£ s. d.
Government of the Commonwealth of Australia 4 per cent Registered Stock, 1955-70, £649 1s. 7d. @ 104½	678 5 9	
Funding Stock, 4 per cent, 1960-90, £200 @ 107	214 0 0	
3½ per cent Conversion Stock, £900 @ 94	846 0 0	
		1738 5 9
NOTE—The above stocks are valued at prices estimated by the Society's brokers.		
Advance for publication of *Weather* Magazine		300 0 0
Advance payments made on behalf of *Weather* Magazine ..		251 11 6
Subscriptions unpaid amounting to £1,121 estimated at ..	650 0 0	
Interest due on deposit in Post Office Savings Bank	7 10 0	
Accounts due for publications	131 3 3	
		788 13 3
Furniture and Fittings	198 13 8	
Instruments	16 8 0	
Estimated value of Society's House, 49, Cromwell Road ..	5375 0 0	
		5590 1 8
Deposit with London Electricity Board		5 0 0
Balance—Cash at Westminster Bank Ltd.		16 7 11
		£8690 0 1

Examined and securities seen,
BALL, BAKER & CO.,
Chartered Accountants.

31 DECEMBER 1949

PAYMENTS

	£ s. d.	£ s. d.
Purchase of £300 2½ per cent Consols		241 11 0
Transferred to General Account		197 0 0
Balance — Cash at Westminster Bank Ltd.*	64 12 11	
Cash on deposit with Post Office Savings Bank ..	5 2 6	
		69 15 5
		£508 6 5

*—The Society holds on account of this Fund —
£800 2½% Consolidated Stock.
£800 3½% Conversion Stock and
£1,200 3% Defence Bonds.

Examined and found correct,
BALL, BAKER & CO.,
Chartered Accountants.

STAFF PENSION FUND,

RECEIPTS

	£	s.	d.
Balance from 1948 — Cash at Westminster Bank Ltd.	41	15	5
Interest on investments	57	5	0
Transfer from General Account	50	0	0
	£149	0	5

17 *January* 1950

RESEARCH FUND,

RECEIPTS

	£	s.	d.
Balance from 1948 — Cash at Westminster Bank Ltd.	26	14	1
Interest received from investments	22	5	0
	£48	19	1

17 *January* 1950

REPAIRS AND MAINTENANCE FUND,

RECEIPTS

	£	s.	d.
Balance from 1948 — Cash at Westminster Bank Ltd.	274	17	6
Interest on Post Office Savings Bank Deposit Account		8	8
	£275	6	2

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31 DECEMBER 1949

PAYMENTS

	£	s.	d.
Gratuity to Mrs. Hayman	10	10	0
Transferred to General Account (Half Pension)	130	0	0
Balance — Cash at Westminster Bank Ltd.*	8	10	5
	£149	0	5

*—The Society holds on account of this Fund —
£300 3½% Conversion Stock,
£800 3½% War Loan and
£750 2½% Consolidated Stock.

Examined and found correct,
BALL, BAKER & CO.,
Chartered Accountants

31 DECEMBER 1949

PAYMENTS

	£	s.	d.
Balance — Cash at Westminster Bank Ltd.*	48	19	1
	£48	19	1

*—The Society holds on behalf of this Fund —
£250 3½% War Loan.
£100 3½% Conversion Stock and
£400 2½% Consolidated Stock.

Examined and found correct,
BALL, BAKER & CO.,
Chartered Accountants

31 DECEMBER 1949

PAYMENTS

	£	s.	d.	£	s.	d.
General Repairs				142	8	0
Balance — Cash at Westminster Bank Ltd.	32	9	6			
Cash on deposit at Post Office Savings Bank	100	8	8			
				132	18	2
				£275	6	2

Examined and found correct,
BALL, BAKER & CO.,
Chartered Accountants

AWARDS,

RECEIPTS

	£ s. d.
Balance from 1948 — Cash at Westminster Bank Ltd.	25 0 0
	£25 0 0

17 *January* 1950

ROYAL SOCIETY PROCEEDINGS FUND,

RECEIPTS

	£ s. d.
Balance from 1948 — Cash at Westminster Bank Ltd.	21 14 11
Deposits received	6 0 0
	£27 14 11

17 *January* 1950

BRITISH RAINFALL ORGANIZATION FUND,

RECEIPTS

	£ s. d.
Balance from 1948 — Cash at Westminster Bank Ltd.	109 0 10
Rent of 62, Camden Square	80 3 4
Dividends and Interest	122 3 6
Sales of *Rainfall Atlas*	2 5 0
	£313 12 8

17 *January* 1950

31 DECEMBER 1949

PAYMENTS

	£	s.	d.
Napier Shaw Prizes	10	0	0
Balance — Cash at Westminster Bank Ltd.	15	0	0
	£25	0	0

Examined and found correct,
BALL, BAKER & CO.,
Chartered Accountants.

31 DECEMBER 1949

PAYMENTS

	£	s.	d.
Cost of reprints of Proceedings	2	12	11
Balance — Cash at Westminster Bank Ltd.	25	2	0
	£27	14	11

Examined and found correct,
BALL, BAKER & CO.,
Chartered Accountants.

31 DECEMBER 1949

PAYMENTS

	£	s.	d.
Payment to tenant for observational work to 31 December, 1949	52	0	0
Insurance	2	0	6
Sundry Expenses	7	5	4
Thermometer purchased from Air Ministry	2	2	0
Administration Expenses transferred to General Account	15	0	0
Telephone	9	7	1
Balance — Cash at Westminster Bank Ltd.*	225	17	9
	£313	12	8

*—The Society holds on behalf of this Fund — £750 3½% War Stock, £100 3% Defence Bonds and £3,097 10s. British Transport 3% Guaranteed Stock, also the Freehold of 62, Camden Square.

Examined and found correct,
BALL, BAKER & CO.,
Chartered Accountants.

PRESIDENT'S FUND,

RECEIPTS

	£	s.	d.
Balance from 1948 — Cash at Westminster Bank Ltd.	13	13	0
	£13	13	0

17 *January* 1950

SYMONS MEMORIAL FUND,

RECEIPTS

	£	s.	d.
Balance from 1948 — Cash at Westminster Bank Ltd.	55	17	4
Cash on deposit with Post Office Savings Bank	50	0	0
Dividends and Interest	30	3	8
	£136	1	0

17 *January* 1950

NAPIER SHAW MEMORIAL FUND,

RECEIPTS

	£	s.	d.
Balance from 1948	376	15	10
Donations received in 1949	33	9	8
Interest on Investment	6	2	6
	£416	8	0

17 *January* 1950

31 DECEMBER 1949

PAYMENTS

	£ s. d.
Balance — Cash at Westminster Bank Ltd.	13 13 0
	£13 13 0

Examined and found correct,
BALL, BAKER & CO.,
Chartered Accountants

31 DECEMBER 1949

PAYMENTS

	£ s. d.	£ s. d.
Symons Medal		17 13 6
Symons Lecture		10 10 0
Balance — Cash at Westminster Bank Ltd. *	56 12 6	
Cash on deposit with Post Office Savings Bank ..	51 5 0	
		107 17 6
		£136 1 0

*—The Society holds on behalf of this Fund —
£650 3½% Conversion Stock and
£123 8s. 8d. 4% Consolidated Stock.

Examined and found correct,
BALL, BAKER & CO.,
Chartered Accountants

31 DECEMBER 1949

PAYMENTS

	£ s. d.
Purchase of £350 3½% Conversion Stock	370 16 4
Balance — Cash at Westminster Bank Ltd.	45 11 8
	£416 8 0

*—The Society holds on behalf of this Fund —
£350 3½% Conversion Stock 1961.

Examined and found correct,
BALL, BAKER & CO.,
Chartered Accountants

Proceedings at meetings of the Society

Ordinary Meeting, 16 November 1949

The election of the following candidates was confirmed :—

Fellows

Halley, Wg. Cdr. James Crawford, D.S.O., 135 Constance Crescent, Hayes, Kent.
Jupp, Wg. Cdr. Basil Barry, 12 Pembridge Gardens, London, W.2.
Lyder, Flt. Lt. Ernest Garth Fidler, D.F.C., R.A.F.V.R., "Basildon," Knoll Road, Bexley, Kent.
Manger, Roy Alfred Sidney, "Martindale," Smallfield Road, Horley, Surrey
Moody, Sqn. Ldr. Ernest, R.A.F., 102 Stanmore Lane, Winchester, Hants.
Thornton, Douglas James, 436 Christchurch Road, Boscombe, Hants.
Tindale, John, 35 Parkside Avenue, Newcastle-upon-Tyne, 7.

Associates

Armstrong, Harold Ross, Aviation Forecast Office, R.C.A.F. Station, Trenton, Ontario, Canada.
Brandon, Ernest William, 84 Emerson Avenue, Toronto, Ontario, Canada.
Bruce, James Philip, Aviation Forecast Office, R.C.A.F. Station, Trenton, Ontario, Canada.
Dewar, Stuart Wilson, Resolute, N.W.T., c/o Eastern Arctic Patrol R.M.S., Ottawa, Ontario, Canada.
Giesbrecht, Arnold, Aviation Forecast Office, R.C.A.F. Station, Trenton, Ontario, Canada.
Grant, A. St. G. G., c/o D.O.T., Goose Airport, Labrador.
Hamilton, Edward James Archibald, c/o Aviation Forecast Office, R.C.A.F. Station, Centralia, Ontario, Canada.
Harrington, James Bishop, Jr., Box 6, Exeter, Ontario, Canada.
Hunt, Charles Frederick, Box 109, Exeter, Ontario, Canada.
McIntyre, Charles Bayard, Box 283, Moncton, N.B., Canada.
Moakler, John Joseph, c/o Aviation Forecast Office, R.C.A.F. Station, Centralia, Ontario, Canada.
Muller, Francis Bernard, c/o Aviation Forecast Office, R.C.A.F. Station, Centralia, Ontario, Canada.
Simla, Joseph, c/o Officers' Mess, R.C.A.F. Station, Greenwood, Kings County, N.S., Canada.

The following papers were read and discussed :

(a) A portable indicating apparatus for the study of temperature and humidity profiles near the ground.

(b) Some estimates of the amount and diurnal variation of evaporation from a clayland pasture in fair spring weather.

By F. Pasquill, B.Sc., F.Inst.P. (See *Q.J.*, Vol. **75**, pp. 239 and 249).

(c) Constant-height balloons — Calculation of geostrophic departures.

By C. S. Durst, B.A. and G. H. Gilbert, B.Sc. (See *Q.J.*, Vol. **76**, p. 75).

Ordinary Meeting, 21 December 1949

The election of the following candidates was confirmed :—

FELLOWS

ALEXANDER, Captain PHILIPOSE, Executive Officer of the T.S. "Dufferin," Bombay, India.

BOCKS, SHIRLEY JOHN, M.A., Cantab., B.Sc., Lond., 182 Skinner's Road North, Kotahena, Colombo 13, Ceylon.

BOYD, RICHARD EDWIN, c/o B.O.A.C., P.O.B. 250 Wingate Avenue, Khartoum, A.E. Sudan.

CARTER, SAMUEL DOUGLAS, B.A., 4 Salisbury Avenue, St. Albans, Herts.

CHANDLER, BERNARD KEMPSFORD, Rest-a-Whyle, Laverstock, Salisbury, Wilts.

CORNISH, REGINALD THOMAS, M.Sc., University College, Gower Street, London, W.C.1.

DAVIDSON, GORDON, c/o B.O.A.C., Wingate Avenue, Khartoum, A.E. Sudan.

DAVIES, JOHN L., M.A., County Planning Dept., Litton Lodge, Clifton Road, Winchester, Hants.

DIGBY, PETER SAKI BARRETT, M.A., University Museum, Oxford.

GARDEN, ROBERT ANDREW, c/o Isdale, 198 Gorgie Road, Edinburgh, 11.

GOWAN, Dr. E. H., University of Alberta, Edmonton, Alberta, Canada.

GUINANE, MAURICE, "Derwen," Ala Road, Pwllheli, Caernarvonshire.

GULLIVER, CHARLES LEONARD, Meteorological Office, Freetown Airport, Freetown, Sierra Leone.

HASTINGS, JOHN DENNIS, "Barracouta," Brisley, Dereham, Norfolk.

HERON, WILLIAM ALEXANDER, 6 Waltham Terrace, Blackrock, Co. Dublin, Eire.

HEWITT, WILLIAM MAYHEW CECIL, 3 Westbrook Road, West Town Park, Brislington, Bristol.

HUGHES, IORWERTH GRIFFITH, Glan Clywedog, Rhewl, Ruthin, Denbighshire.

JENKINS, ERIC, The Hollies, Tinsley Lane, Three Bridges, Sussex.

JESSUP, ERNEST HENRY, 25 Bradford Avenue, Cleethorpes, Lincs.

KILNER, Sqn. Ldr. JOSEPH RICHARD, D.F.C., 46 Clockhouse Road, Beckenham, Kent.

LANCASTER, COLIN, 23 Glebe Avenue, Easington, Co. Durham.

LORAINE, Captain ANTHONY CHRISTOPHER, 56 Ovington Street, London, S.W.3.

MCKAY, HUGH HAMILTON, 351 West Road, Newcastle-on-Tyne, 5.

MCWILLIAM, WILLIAM REA, 110 Waterfall Road, Southgate, London, N.14.

MARSHALL, ALFRED HENRY, "Goonvrea," Kings Head Lane, Bristol 3.

MIREHOUSE, Colonel HENRY WILLIAM, M.B.E., Myresyke, Ruan Minor, Helston, Cornwall.

MITCHELL, JAMES HUME, Neville Cottage, Haughton Road, St. Ives, Huntingdonshire.

MOCKLER, WILLIAM, High Street, Long Crendon, Aylesbury, Bucks.

RANDALL, Captain C. A., c/o Lloyds Bank, Chowringhee, Calcutta, India.

RAO, NELANUTHALA SUBRAHMANIAM SUBBA, M.A., 46/47 Kensington Garden Square, Bayswater, London W.2.

RODRIGUES, JERVIS CYRIL, B.Sc., 61 Military Road, P.O. Santa Cruz, Bombay 25, India.

SCORER, RICHARD SEGAR, M.A., 2 Stanton Road, London, S.W.20.

TALJAARD, JOHANNES JOCHEMUS, M.Sc., 1 Nevern Road, London, S.W.5.

TEMPLE, PETER JAMES, M.B.E., 9 Pollards Hill, Limpsfield, Surrey.

TROTTER, ROBERT MARTIN, BM/RMT, London, W.C.1.

VARDON, PHILIP JOHN, 4 Brook Road, Fishponds, Bristol.

WALTON, GORDON FRANCIS, M.A., Lincoln College, Oxford.

WOOD, CLIFFORD WILLIAM DONALD, Beechwood, 73 Morton Gardens, Wallington, Surrey.

WORTHINGTON, ARTHUR AGNEW, 78 Elmstead Avenue, Wembley, London.

Foreign Members

Chalker, William Rogers, Department of Meteorology, Massachusetts Institute of Technology, Cambridge 39, Mass., U.S.A.
Findiklís, Dr. Theóklitos Th., 13 Psarron Street, Athens, Greece.
Hassanein, Saïid Abd El-Monim, Meteorological Department, Ministry of War and Marine, Cairo, Egypt.
Houghton, Prof. Henry G., 29 Edmunds Road, Wellesley Hills 82, Massachusetts, U.S.A.
Larkin, Harry H., Jr., 189 Van Ronsselaer Street, Buffalo 10, New York, U.S.A.
Neiburger, Prof. Morris, University of California, Los Angeles 24, California, U.S.A.
Rigby, Malcolm, 5816 22nd Street N., Arlington, Virginia, U.S.A.
Shapiro, Ralph, B.Sc., M.S., Massachusetts Institute of Technology, Cambridge 39, Massachusetts, U.S.A.
Vaughan, Harry, 54 Oakley Road, Belmont, Massachusetts, U.S.A.
Wexler, Raymond, Meteorology Department, Imperial College of Science, London, S.W.7.
White, Robert M., B.A., M.S., Massachusetts Institute of Technology, Cambridge 39, Massachusetts, U.S.A.

Associates

Henderson, John, Meteorological Office, Vancouver A.M.F., B.C., Canada.
Kennedy, Gerald Bruce, Aviation Forecast Office, M.P.O. 1015, Churchill, Manitoba, Canada.
Levick, Rodney Beeton Murray, c/o Dominion Bank, Victoria, B.C., Canada.
McIsaac, John Francis, Meteorological Section, R.C.A.F. Station, Summerside, P.E.I., Canada.
Titus, Robie Leslie, Main Meteorological Office, Goose Airport, Labrador.

Student Associates

Johnson, Arnold Irvine, 70 Kimberley Road, Chingford, London, E.4.
Rogers, Miss Ruth Helen, B.Sc., 5 Fairfax Road, Bedford Park, London, W.4.
Summers, Peter W., Drayton Road, Belbroughton, nr. Stourbridge, Worcs.

The following papers were read and discussed :

(a) The composition of coagulation elements in cumulonimbus.
By F. H. Ludlam (See *Q.J.*, Vol. **76**, p. 52).

(b) Air motion ahead of warm fronts.
By M. K. Miles, M.Sc. (See *Q.J.*, Vol. **75**, p. 399).

Ordinary Meeting, 25 January 1950

The election of the following candidates was confirmed :—

Fellows

Clackson, James Royden, Meteorological Office, Ikeja, Lagos, Nigeria, West Africa.
Crabtree, John, 47 Belfield Old Road, Rochdale, Lancs.
Dent, Eric Dixon, Meteorological Office (MO. 20), Headstone Drive, Harrow, Mddsx.
Gilchrist, Andrew, M.A., 1 Glen Crescent, Darvel, Ayrshire.
Hayman, Mrs. Winifred H., " Timbers," 32a Hazlewell Road, Putney, London, S.W.15.

HONOUR, HERBERT JEFFERY, Kano, Nigeria, West Africa.
JACKSON, STANLEY P., University of Witwatersrand, Johannesburg, South Africa.
PORTER, KEITH ALAN, Sqdn/Ldr., 32 Silverdale Road, Petts Wood, Kent.
SPOONER, ANTHONY, 74 Downs Park East, Westbury Park, Bristol, 6.
TIMMIS, NIGEL ANTHONY, The Gables, 21 Broad Lane South, Wednesfield, Wolverhampton, Staffs.
WATKINS, MONTAGUE, Stagg Farm, Flaunden, nr. Hemel Hempstead, Herts.

ASSOCIATES

DOLAN, MATTHEW F., 8 Faulker Street, Dartmouth, Nova Scotia.
FOSTER, LAMONT BALCOM, Meteorological Office, R.C.A.F. Station, Greenwood, Nova Scotia.

STUDENT ASSOCIATES

LORTON, ROBERT GEOFFREY, Crohamhurst, 24A Grange Road, Eastbourne.
ROSS, JAMES D., "Kirkview," Uphall, West Lothian, Scotland.

Annual General Meeting, 25 January 1950

Sir ROBERT WATSON-WATT, C.B., F.R.S., President, in the chair.

The Minutes of the Annual General Meeting on 26 January 1949, were confirmed.

The President said that it was his duty in presenting the Report of the Council for the year 1949 at this Annual General Meeting to refer to a number of misprints ; the Treasurer in particular was in a position of some difficulty because both the Accounts and the Report came so close together, and the Treasurer, the Honorary Secretaries and the staff were to be congratulated on the work which had been done to enable the accounts to be available at such an early date.

The President then proceeded to comment briefly on the salient points contained in the Report. The numerical strength of the Society remained virtually unchanged since the last Annual General Meeting, and it was a source of gratification to note that the Society was able to maintain its membership at more than double the pre-war figure — there were some 810 members at the end of December 1938 and 1,654 at the end of December 1949. He recorded with deep regret a rather long obituary list, included in which were names of valuable members whose loss will be keenly felt by the Society ; special mention had already been made of the late Mr. Wm. Dunbar, who served the Society so well from 1937 to 1945 and did so much for the Scottish Centre ; Mr. G. A. Clarke, who would be so well remembered for his cloud photographs, and whose valuable collection was now in the possession of the Society.

Referring then to publications, Sir Robert said that all members were painfully aware of the difficulties of overtaking arrears of publication of the *Quarterly Journal*, but that by diligent effort on the part of the Editor and the Editing Committee these arrears had now been virtually overtaken ; the achievement must be specially gratifying to Dr. Sutcliffe and his co-operators in this large enterprise which they undertake for the Society. The *Journal* had just about doubled the number of communications compared with pre-war years. Turning to the magazine, *Weather*, he showed that the Society had had the advantage of the services of a succession of Editors in order to widen its very extensive appeal, some continuing and others having resigned ; acknowledgment of their services had been recorded in the Report. The President felt bound to say personally that he was impressed by the tributes paid to *Weather* as a journal, not only by Members in this country but by Members in Canada, the United States and by a number of people in the United Kingdom

who were not Members. It did not of course detract from our appreciation of the incomparable value of the *Quarterly Journal*. He regarded the addition of *Weather* as a notable step in the Society's responsibility to the public and in the furtherance of meteorology.

There had been several changes in the staff of the Society. Council had already expressed its thanks to Cdr. Burgess, but he would like at this Annual General Meeting to take the further opportunity of thanking Commander Burgess for the work which he did as Executive Secretary and for the very large amount of work which he had continued to do so nobly since he took up his new activities. The new Assistant Secretary, Mr. M. E. Shoenberg, had been with the Society long enough to confirm the high opinion which the Selection Committee formed when recommending his appointment ; during 1950 he and his staff would be submitted to a performance test which would stretch them very little short of the elastic limit. We should, at the end of this year, have no one left on our paid staff who was with us at the beginning of last year — Mrs. Cook, the sole survivor, would be leaving us very soon, and on behalf of the Society he would like to record our appreciation for the work which she had done for us as the clerk for *Weather*.

The Library was a tender spot on the conscience of the Council ; owing to wartime conditions it was not now in a state in keeping with the dignity of such a unique collection. Dr. Brooks had to resign his duties as Honorary Librarian a year ago. We had the greatest hope that we should continue to have his advice until we were able to appoint someone to fill this vacancy in the not too distant future. There was a great deal of work to be done to make the Library worthy of itself and it was hoped that the re-organisation would be well forward before the Centenary Celebrations. The Society would welcome any voluntary assistance on the manual side to get the books in proper order and an appeal would be made through the Assistant Secretary.

It was gratifying, he said, that we had members who were Phenological Observers and that observations were being maintained although the report was not at the present time being published by the Society. The future of the Phenological Report would engage the attention of the new Council.

The President then referred to the Clarke Collection which the Society had been so fortunate in acquiring ; some of these well-nigh unique photographs, he added, would be hung in the entrance hall of the Society's Offices during the Centenary Celebrations. He also referred to the very generous donation by Mr. C. J. P. Cave, whom Members were delighted to have with them on this occasion — to be thanked for the many things which he has done not only for the Society but also for meteorology.

Sir Robert invited the Treasurer to remark upon the financial part of the report, adding that he anticipated one question in the minds of Fellows — namely, changes in the By-Laws which were very much in need of bringing into better order. The question, however, was not a neglected one ; it would be an under-statement to say the revision was a complex task and it was hoped that a revised set of By-Laws would be presented in the life of the new Council.

Treasurer's Statement

The Treasurer, speaking to supplement the formal statement appearing in the Council Report with regard to Finance, said that it would be seen from the printed accounts that the liquid funds in hand on the General Account amounted to only £24 at the end of the year 1949, and that there were bills due for payment amounting to £645. Moreover, the general reserves built up during the war period had now all been utilised ; so that funds were back as at 1939.

Income from annual subscriptions showed a considerable decline, due largely to accumulation of arrears, a large fraction of which, it was feared, would prove irrecoverable.

With regard to expenditure, apart from the amounts related to past commitments, printing had been a specially heavy item (£260) chiefly on account of the issue of a much needed and long overdue List of Members, which cost in round figures £150.

The cost of producing the *Quarterly Journal* seemed settled at about £2,000 per annum ; but the cost of providing *Weather* free to members had been much reduced by the assiduous efforts of the Committee entrusted with its production and might be anticipated as about £400 in future.

The Salaries bill had again substantially risen. It was a matter of common knowledge that efficient service was no longer obtainable at anything like the figures to which one had become accustomed, and the situation created thereby gave cause for great concern.

There were important non-recurring items on both sides of the accounts. The cost of purchasing Mr. Clarke's cloud negatives and prints was partially offset by the sale of our complete file of the issues of *Nature* dating back to the 1870's.

Although the general reserves had been severely tapped, it was satisfactory to note that two special and important reserves existed (in addition of course to the valuable freehold property in which the Society meets) which had not hitherto been subject to capital diminution — namely the Life Composition and Staff Pension Funds. This year, however, Council had considered it necessary to draw upon *both* to a small extent. £1 for each compounded Fellowship (£197 in all) had been taken from the first-named, and 50 per cent of the pension paid to a former Assistant Secretary had been drawn from the second.

It was his disagreeable duty to direct attention to the unfavourable financial position now existing. Were it not for the generous allocations made to the Society from the Government Publications Grant-in-aid Funds, the situation would be serious indeed.

Economies were being effected wherever practicable — the discontinuance of the *Phenological Report* and the *Bibliography of Meteorological Literature* for example — but it was evident that a substantial addition to income must be found very quickly. Increased membership would be a practical step.

The President then moved that the Report be received and adopted and be printed in the *Quarterly Journal.*

Mr. Ludlam moved that the comments by the President on the work done by the Treasurer and Honorary Secretaries be endorsed by the members. The motion for adoption of the Report was carried unanimously.

Professor Sir David Brunt proposed a vote of thanks to the President and the 1949 Council, and did so, he said, with very great pleasure. He had been associated with Council for a long time and was well aware of how much labour membership of Council involved ; indeed if any Fellow had any doubts on this point he would say that their deliberations had often robbed Councillors of their cup of tea — and no more clear-cut evidence was required. This had been a busy day for everybody and it was not for him to make a long speech. He would, however, like to say that there was evidence in the Report presented to the Society to show that the Council must indeed have put in a great deal of work ; it was a most gratifying report and it pleased him to see the names of so many new contributors to the *Quarterly Journal*, and to *Weather*, the extremely active new journal. He said he would like to pay tribute to one for whom he had considerable fellow feeling — Dr. Sutcliffe, Editor of the *Q.J.* He was gratified to see that Professor Sheppard had taken the Chair left vacant by Dr. Sutcliffe's departure from that office. Sir David said he was the first to accept the designation of Editor, and the best way in which the *Journal* could be run was for someone to take the responsibility. Members owed Dr. Sutcliffe a very great dept ; he had filled the *Quarterly Journal* with a great deal of interesting material — material difficult to assess at this stage, but possibly more likely to be acclaimed in 15 years' time. In expressing his pleasure in the reading of the *Quarterly Journal*, he would like to propose a vote of thanks to Dr. Sutcliffe and the Council of 1949. This was seconded by Capt. W. N. McClean.

The President said the generous terms in which this motion was proposed and carried were sincerely appreciated.

At this stage the President asked Mr. Whiten and Cdr. Burgess to collect the Balloting Lists for Council.

Sir Robert then referred to the Awards made by the Society during this Session ; Council were of the opinion that since we were about to celebrate the 100th birthday of the Society we should depart from customary procedure in relation to these awards, normally to be handed over at this Annual General Meeting, and proposed that formal presentations should be made at the Centenary Meeting on 3 April. He then drew attention to the Hugh Robert Mill Medal and prize which Council had decided to initiate on the recommendation of the British Rainfall Organization Fund Committee ; the first award of this would be to Dr. Hugh R. Mill himself, who was President of the Society in 1907 and 1908.

Council, Sir Robert stated, had recommended for approval by the Society that the first Hugh Robert Mill Medal should be displayed during our Centenary Celebrations ; there were of course the normal difficulties of production and delivery. It had been agreed that the President and Officers, as soon as might be possible after the Centenary meeting, should visit Dr. H. R. Mill to make the presentation and convey to him the warmest good wishes of his colleagues in the Society.

The following citations were announced :

(a) Buchan Prize, in respect of the period 1944 — 1948.

1. To Reginald Cockcroft Sutcliffe, O.B.E., Ph.D., for his outstanding contribution to the study of vertical motion in relation to the atmospheric fields of pressure and temperature, as given in his paper, " A contribution to the problem of development," (*Quart. J. R. Met. Soc.*, Vol. **73**, p. 370).

2. To Charles Henry Brian Priestley, M.A., F.Inst.P., for contributions to the study of dynamical meteorology contained in the following papers which have appeared in the *Quarterly Journal* of the Society, " On the frictional influence of horizontal wind shear on vertical motion," (Vol. **72**, p. 284) ; " Dynamical control of atmospheric pressure, I " (Vol. **73**, p. 65) ; " Dynamical control of atmospheric pressure, II " (Vol. **74**, p. 67) ; and (in joint authorship), " An investigation of subsidence in the free atmosphere," (Vol. **73**, p. 43).

(b) Hugh Robert Mill Medal and Prize :

To Hugh Robert Mill, D.Sc., LL.D., for his outstanding contributions to the science of meteorology with particular reference to rainfall as detailed in the following summary of his career.

Hugh Robert Mill was Director of the British Rainfall Organization and Editor of British Rainfall and Symons's Meteorological Magazine from 1901 until he retired in 1919, when the Organization was incorporated in the Meteorological Office.

During this period he applied his authoritative geographical knowledge and his experience to open up new lines of research in the study of rainfall over the British Isles. In addition to reports included in British Rainfall and Symons's Meteorological Magazine he contributed, between 1904 and 1916, chapters on the rainfall of various counties to the Geological Survey Memoirs and set out the results of some of his researches in other papers, including the following :

On the distribution of mean and extreme annual rainfall over the British Isles. (*Proc. Inst. Civ. Eng.*, London, Vol., **155**, p. 1).

Map-studies of rainfall. (*Quart. J. R. Met. Soc.*, London, Vol. **34**, p. 65).

Report on the rainfall in the Exe Valley. (*Geogr. J.*, London, 1909, p. 630).

Unprecedented rainfall in East Anglia, Aug. 25-26, 1912. (*Quart. J. R. Met. Soc.*, Vol. **39**, p. 1).

Isomeric rainfall maps of the British Isles (with Carle Salter). (*Quart. J. R. Met. Soc.*, London, Vol. **41**, p. 1).

Already distinguished as a geographer and for his knowledge of the Antarctic, Hugh Robert Mill also became the authority on British rainfall and was consulted by Government Departments and other bodies. He aroused great interest in this subject by his fascinating presentation of the facts, and of their interpretation, in lectures and in contributions to scientific journals. He was a source of inspiration in rainfall research. His work was of great importance in many practical aspects of climatology, agriculture, water supply and water power, as well as in pure science.

(c) Darton Prize :

1. Rodney B. M. Levick, for his paper " 50 years of English weather " (1949) *Weather*, London, Vol. **4**, page 206.
2. James M. Craddock, M.A., for his paper " The development of cumulus cloud " (1949), *Quart. J. R. Met. Soc.*, London, Vol. **75**, page 147.

Sir Robert Watson-Watt then delivered the Presidential Address, his subject being " The evolution of meteorological institutions in the United Kingdom."

Mr. C. J. P. Cave proposed a vote of thanks to the President for his address and asked that he allow the address to be printed in the *Quarterly Journal*. It was a most stimulating address and he congratulated the Society on having Sir Robert as its President. Alluding to Sir Robert's having termed him his " father-in-meteorology," Mr. Cave said he had good reason to feel proud of his " child."

Flt. Lt. D. J. Schove said it was a pleasure and an honour to second the vote of thanks to Sir Robert Watson-Watt so ably proposed by Mr. Cave. He endorsed the sentiments that had already been expressed about the President and added that he had remembered Sir Robert's voice from his schooldays when he had greatly enjoyed listening to his radio talks on meteorology. It was partly due to Sir Robert that his interest had originally been aroused and that he had then joined the Society. Mr. Schove said that for a long time Sir Robert's meteorological work had been carried on elsewhere but that recently he had been able to enjoy the pleasure of hearing him at the Society. His Presidential address had inspired everyone with the determination to demand the best for the country in the furtherance of meteorological research and progress. He was glad to second Mr. Cave's motion that the thanks of the Society be given to our President.

Sir Robert then announced the result of the Ballot, which was in accordance with the Balloting List already distributed to the meeting and confirmed the election of the following members to Council :—

President

Sir Robert Watson-Watt, C.B., F.R.S.

Vice-Presidents

Leo Claude Wallace Bonacina
Gordon Miller Bourne Dobson, M.A., D.Sc., F.Inst.P., F.R.S.
Eric Ludlow Hawke, M.A.
Reginald Cockcroft Sutcliffe, O.B.E., Ph.D.
Andrew Thomson, O.B.E., M.A. (For Canada).
Sir Ernest Maclagan Wedderburn, O.B.E., D.Sc., LL.D., D.K.S. (For Scotland)

Treasurer

William Moody Witchell, B.Sc.

Secretaries

Wing Commander Robert Martin Poulter, O.B.E.
Percival Albert Sheppard, B.Sc., F.Inst.P.

Scottish Secretary

James Paton, M.A., B.Sc., F.R.S.E.

Foreign Secretary

John Samuel Forrest, M.A., D.Sc., F.Inst.P., A.M.I.E.E

Editor

Percival Albert Sheppard, B.Sc., F.Inst.P.

Councillors

Oliver Martin Ashford, B.Sc., A.Inst.P.
John Kernan Bannon, B.A.
David Duncan Clark, M.A.
Percy Robert Crowe, Ph.D.
Richard Meade Goody, M.A.
George Cunliffe McVittie, O.B.E., M.A., Ph.D.
Alfred Roger Meetham, D.Sc.
Cameron Darrell Ovey, B.Sc., F.G.S.
Howard Latimer Penman, Ph.D., F.Inst.P.
James Martin Stagg, O.B.E., M.A., D.Sc.
Oliver Graham Sutton, D.Sc., F.R.S.
Inst. Cdr. Frank Lorimer Westwater, M.A., R.N.

The President then said he would like to read to this meeting a resolution passed by Council some three hours ago. On the termination of his period of service in the Office of Honorary Secretary to the Royal Meteorological Society, the Council wished to express to Mr. E. L. Hawke by resolution their highest appreciation of his unsparing work for the welfare of the Society during the years from 1935 to 1949, which included the difficult war period, and in order to signify this appreciation directed that he be enrolled among the Life Fellows of the Society under By-Law Section X.8. Mr. Hawke had been associated with him for some time and it was a great pleasure to him at this moment to say, on behalf of members and the Council, to Mr. Hawke that they were conscious of all the services he had rendered to the Society, and were very gratified to know that he would be continuing as a Vice-President. He could not leave the matter at this point without referring to Mr. Hawke's Honorary Secretaryship during the war years ; but for his labours this Society might have been in a very powerless condition indeed during that period.

Mr. E. L. Hawke in responding, said that he was deeply grateful to Sir Robert for his kindly remarks, to the Council for their most generous action, and to the meeting for the applause with which the announcement of the Council's resolution had been received. He very greatly appreciated the honour of having been allowed to serve the Society as Secretary under the presidency of his former colleague Sir Robert Watson-Watt and of half a dozen other distinguished meteorologists, several of whom he was happy to see present that evening. He had felt it a high privilege to be so closely associated with them all in working for the Society's welfare. In his capacity as Secretary he had enjoyed the opportunity of making many good friends among the rank and file also. He would always look back on his 15 years of office with gratitude and pleasure.

The meeting was declared closed at 7.10 p.m.

Obituary

Mr. C. A. BELL

We have to record the death on 28 January 1950, in his 72nd year, of Charles Albert Bell, who resided latterly at Kebroyd Hall, Triangle, near Halifax, Yorkshire. From his youth onwards Mr. Bell had taken a keen interest in various branches of science — astronomy in particular. When only 21 years of age he was giving lectures on this subject, illustrated by lantern slides made from his own drawings of celestial bodies. Later he helped to found the Astronomical Society of Hull. It was meteorology, however, that had chief claims on his attention after he retired from the Civil Service in 1940. For several years during the war he held the appointment of Acting Borough Meteorologist at Southport. The high standards and traditions of the Fernley Observatory were ably maintained by him during the absence of Mr. G. A. Lidster on meteorological duties with the Royal Air Force. Thenceforward Mr. Bell's services as a lecturer on weather and the climate of northern England were much in demand. He was elected a Fellow of this Society on 20 December 1944, during his term of office at Southport.

E.L.H.

Mr. J. REES, F.I.C.S., F.R.A.S., F.R.G.S.

By the death on 9 May 1949, after a long illness, of John Rees the Society lost a Fellow of 36 years' standing. A chartered secretary by profession, Mr. Rees was a man of wide interests. He held membership in 13 corporate bodies, among which were the Royal Society of Arts, the Royal Scottish Geographical Society, and the American Museum of Natural History. Much of his time was devoted to observational astronomy and meteorology. He served formerly as registrar of the Astronomical Society of Wales, and for many years maintained a well equipped climatological station in the grounds of his Penarth home. Mr. Rees was also prominent in the world of freemasonry, attaining the rank of Provincial (Mark) Grand Secretary for the whole of South Wales.

E.L.H.

Miss E. L. RAMSAY

We have to record the death at her Berwickshire home on 23 October 1949 of Miss Elizabeth Lucy Ramsay. Miss Ramsay, who was a native of Islay, had resided for the last 38 years at Stainrigg, near Coldstream, where she was well known as a keen sportswoman and rider to hounds. Elected a Life Member of the Scottish Meteorological Society in 1906, she had held Fellowship in the Royal Meteorological Society since the fusion of the two bodies in 1921.

E.L.H.

The Reverend J. P. ROWLAND, S.J., B.Sc.

The Reverend James Peter Rowland, whose death in his 73rd year occurred on 26 December 1948, was one of the many able devotees of natural science to be numbered among Jesuit Fathers. He joined the Society of Jesus as a youth of 19 in 1894 and was ordained priest in 1910 after taking the University of London B.Sc. degree in the course of his studies. Before coming permanently on the staff of Stonyhurst Observatory, to which he was appointed in 1919 as assistant to Father Cortie, he had taught at two or three colleges of the Society and had spent a year in research at Oxford. In 1932 he succeeded Father E. O'Connor as Director of the Observatory, a post which he held until ill health compelled his retirement at the close of 1947.

Father Rowland was best known in the scientific world as a seismologist. His success in promptly locating the epicentres of earthquakes was remarkable in view of the limited instrumental equipment at his disposal. Among his other duties at the Observatory were the routine magnetic work and solar observations, as well as occasional planetary studies. On these subjects he contributed valuable papers either to the Royal Astronomical Society or to the British Association.

It was as a weather forecaster, however, that Father Rowland made his name among the populace of northern England. Born and bred in Lancashire, he had familiarised himself with the climatic characteristics of the county to such good effect and developed so acute a " weather sense " that he was enabled to amplify or modify very usefully the more generalised findings of the official forecasters at headquarters. For many years the predictions issued by the Stonyhurst Observatory over his name were regularly published in Lancashire newspapers, and thanks to the combination of local knowledge with scientific training and assiduous observation which underlay them they won a high reputation for accuracy and utility. Father Rowland's Fellowship in this Society dated from 15 February 1933.

E.L.H.

Professor J. H. M. WEDDERBURN, F.R.S.

Joseph Henry Maclagan Wedderburn, emeritus professor of mathematics, Princeton University, who died at his Princeton home on 9 October 1948 in his 67th year, was among the members of the Scottish Meteorological Society who were transferred to the Royal Meteorological Society on the amalgamation in 1921. Born at Forfar, he received his education in Edinburgh, where he graduated in 1903. The same year saw his election to Fellowship of the Royal Society of Edinburgh. After taking post-graduate courses at Leipzig, Berlin and Chicago he returned to his native land and held the post of assistant to Professor George Chrystal from 1905 to 1909. By the age of 25 he had made a classical contribution to the theory of semi-simple algebras. In 1909 Wedderburn left Edinburgh to join the mathematical faculty at Princeton University. On the outbreak of the 1914-18 war he enlisted as a private in the Seaforth Highlanders. Later he took command of an observation group in the Royal Engineers and was mentioned in dispatches. Soon after the conclusion of hostilities he resumed his work at Princeton : he was assistant professor of mathematics in 1921-23, associate professor from 1923 to 1928, and finally full professor until his retirement in 1945.

Wedderburn's researches into hypercomplex numbers brought him the award of the Makdougall-Brisbane Prize by the Royal Society of Edinburgh in 1921. For nearly 20 years he acted as editor-in-chief of the *Annals of Mathematics* : it was largely through his skilled guidance that this publication, the responsibility of Princeton University from 1911 onwards, attained its present eminence among the world's mathematical periodicals. In 1933 Wedderburn was elected to Fellowship of the Royal Society. His interest in meteorology was of long standing. While still an undergraduate he spent a summer vacation as voluntary observer at the Halfway hut on Ben Nevis.

E.L.H.

Notes

Notes

Publications of the Meteorological Office

British Rainfall, 1947

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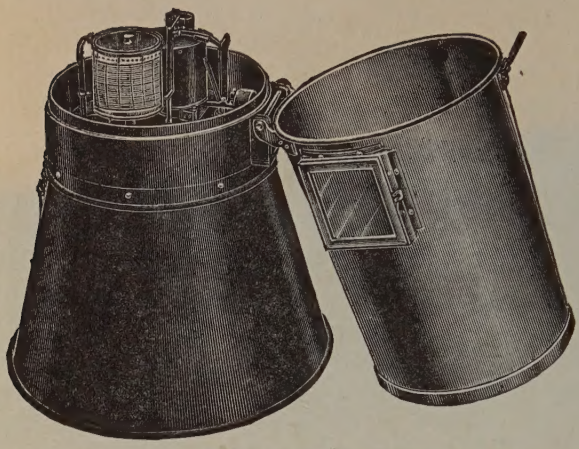

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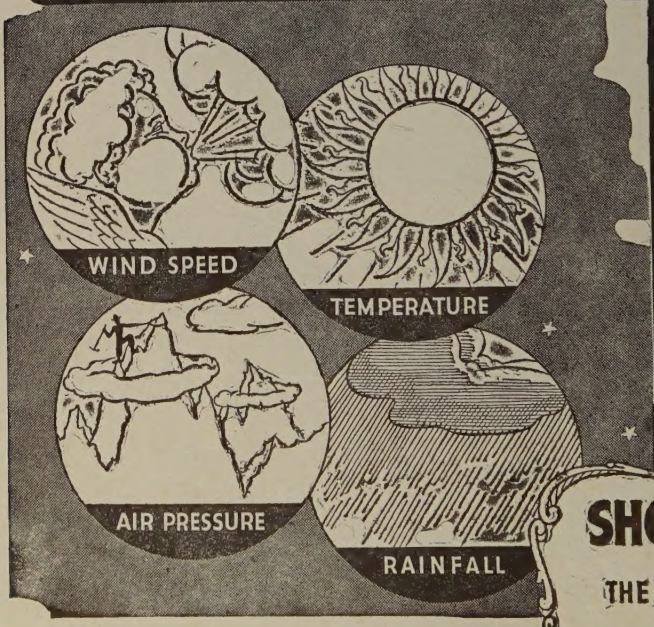

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